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Condition Based Maintenance Literature Survey

Tamara Keating, Tamara McLaughlin and Sharon Weaver

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Defence R&D Canada – Atlantic

Contract Report
DRDC Atlantic CR 2012-106
October 2012

Canada

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Abstract

The goal of this document is to provide Condition Based Maintenance (CBM) stakeholders with a solid perspective on the state-of-the-art of CBM and to inform the Canadian Forces on the potential of CBM and Autonomic Logistics (AL) practices for improved military platform performance and cost effective platform life cycle management. Two databases of 4,394 bibliographic records of journal articles, conferences papers, theses and government reports (2006-2011) and 1,204 patent families (1990-2011) were compiled and analyzed using text analytic software. Findings show that CBM research is primarily engaged with technical challenges related to sensor technologies, condition monitoring, and diagnostic and prognostic accuracy. Communications and decision support technologies are also receiving increased attention. The benefits of CBM are substantial and could represent significant cost-efficiencies in the long-term. However, short-term benefits are difficult to realize since initial acquisition and installation costs are high. Careful consideration must be paid to data integration with legacy systems, particularly supply chain management and logistics systems. Work on the Joint Strike Fighter (JSF) is advancing development of prognostics and health management (PHM) methods as well as the related logistics systems, and is an important area to monitor as lessons learned for the JSF could be applied to retrofitting legacy platforms.

Résumé

Le présent document a pour but de fournir aux intervenants de la maintenance selon l'état (MSE) un tour d'horizon fidèle des derniers avancements dans ce domaine, ainsi que d'informer les Forces canadiennes (FC) sur les pratiques possibles en matière de MSE et de logistique autonome (LA) menant à des plateformes militaires plus performantes et à une gestion rentable de leur cycle de vie. Deux bases de données, l'une comptant 4 394 registres bibliographiques d'article de périodiques, de communications de conférence, de thèses de doctorat et de rapports gouvernementaux (2006-2011) et l'autre plus de 1 204 familles de brevets (1990-2011), ont été compilées et analysées au moyen de logiciels d'analyse textuelle. Les résultats montrent que la recherche en MSE fait surtout face à des défis touchant les technologies des capteurs, la surveillance de l'état et l'exactitude des diagnostics et des pronostics. L'on constate également que les technologies de la communication et de l'aide à la prise de décision retiennent de plus en plus l'attention. Les avantages de la MSE sont indéniables et peuvent se traduire par des économies substantielles à long terme. En revanche, les avantages à court terme sont hypothéqués par l'importance des coûts initiaux d'acquisition et d'installation. Il faut examiner soigneusement l'intégration des données avec les systèmes existants, en particulier ceux de la gestion de la chaîne d'approvisionnement et de la logistique. Les travaux portant sur le chasseur Joint Strike Fighter (JSF), qui favorisent l'élaboration de méthodes de pronostic et de gestion de l'état et le développement des systèmes de logistique connexes, sont un terreau fertile à surveiller en termes de leçons retenues, puisqu'on pourrait en appliquer les résultats à la modernisation des plateformes existantes.

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Executive summary

Condition Based Maintenance Literature Survey

Tamara Keating, Tamara McLaughlin, Sharon Weaver; DRDC Atlantic CR 2012-106; Defence R&D Canada – Atlantic; October 2012.

Background: Defence R&D Canada (DRDC) is interested in assessing the potential impact that Condition Based Maintenance (CBM) and Autonomic Logistics (AL) would have on the Canadian Forces (CF) operations and on the ability of the Royal Canadian Air Force (RCAF) to address its S&T implementation directives (2010). In response, DRDC commissioned a Strategic Technical Insights (STI) study through the National Research Council (NRC) with the objective to increase the CF understanding of CBM and to inform stake holders, policy makers and decision makers on CBM potential in the CF. This objective is met by addressing the following: The state of CBM/CBM+ Technologies and Concepts of Operation, The linkages between CBM and its variants (e.g. IHM, S&RL, PHM, Autonomic Logistics, etc.), the benefits of CBM/CBM+, particularly with regards to Return On Investment (ROI).

Results: A database of 4,394 bibliographic records of journal articles, conferences papers, theses and government reports, published between 2006 and 2011, was compiled and analyzed using text analytic software. In addition, records for 1,204 patent families were also gathered and analyzed (1990-2011). Over 60 articles, market research reports and government documents were also reviewed. Analysis revealed that there is a high degree of patenting activity for automotive applications, such as vehicle telematics related to condition of the vehicle or driver, but that condition based maintenance for other industries is somewhat less mature. Operational and technical interoperability among systems and across nations is not widely discussed in the literature, except in the context of open standards for sensor and data interoperability; however there is currently no industry consensus on which standards to follow. Careful selection of standards and consideration of data formats and integration with legacy data should be considered for any CBM implementation.

Drivers for the adoption of CBM are the same as the cited benefits: to enhance safety, to improve business and maintenance processes, and to reduce operational and support costs. In general, cost savings are usually calculated from cost avoidance based on reductions in maintenance test flights, maintenance man hours, reduced system downtime, and reduced costs in spare components. The preparation of a CBA becomes a task of determining the cost differences between the platforms with and without CBM and therefore historical cost and maintenance data must be available for comparison. Of the studies examined, all but one found significant cost savings, sometimes in the millions of dollars, and a positive return on investment (ROI). However, the ROI sometimes takes years to realize and initial investment may be difficult to justify. Observed barriers and challenges to CBM implementation include: High acquisition and installation costs – as much as $15,000 USD per platform, Prognostic accuracy and selecting appropriate prognostic methods – improvements to sensors and analytical algorithms are still needed to reduce false alarms.

Significance: This Strategic Technical Insight Analysis (STIA) is expected to help increase the Canadian Forces' understanding of key CBM drivers, issues, benefits and challenges and to help fine tune its efforts in the development of a Canadian CBM strategy/policy.

Future plans: Conduct a sound cost-benefits analysis pilot study, establish a community of interest (COI) and initiate the development of a CF CBM strategy.

Sommaire

Condition Based Maintenance Literature Survey

Tamara Keating, Tamara McLaughlin, Sharon Weaver; DRDC Atlantic CR 2012-106 ; R et D pour la défense Canada – Atlantique; octobre 2012.

Contexte : Recherche et développement pour la défense Canada (RDDC) souhaite évaluer les répercussions possibles de la maintenance selon l'état (MSE) et de la logistique autonome (LA) sur les opérations des Forces canadiennes (FC) et sur la capacité de l'Aviation royale du Canada (ARC) de satisfaire aux exigences de ses directives de 2010 sur la mise en œuvre des sciences et des technologies (S et T). Par conséquent, RDDC a commandé une étude de données techniques stratégiques au Conseil national de recherches du Canada (CNRC) pour permettre aux FC de mieux comprendre la MSE et pour renseigner les intervenants, les responsables des politiques et les décideurs sur le potentiel de la MSE au sein des FC. Pour y parvenir, il faut tenir compte des aspects suivants : l'état actuel des technologies de MSE/MSE+, les concepts d'opération, les liens entre la MSE et ses variantes (soit le contrôle intégré de l'état, la logistique de détection et d'intervention, le système de pronostic et de gestion de l'état, la logistique autonome, etc.) et les avantages de la MSE/MSE+, en particulier au chapitre du rendement du capital investi (RCI).

Résultats : Une base de données, qui réunit 4 394 registres bibliographiques d'article de périodiques, de communications de conférence, de thèses de doctorat et de rapports gouvernementaux publiés de 2006 à 2011, a été compilée et analysée au moyen de logiciels d'analyse textuelle. De plus, les registres de 1 204 familles de brevets ont également été recueillis et analysés (1990-2011). Plus de 60 articles, rapports d'étude de marché et documents gouvernementaux ont eux aussi été examinés. L'analyse de cette information a révélé un grand nombre de demandes de brevets déposées pour des applications liées à l'automobile, comme les dispositifs télématiques à bord qui évaluent l'état du véhicule ou de son conducteur, mais cette technologie de la maintenance selon l'état n'a pas autant progressé dans d'autres secteurs de l'industrie. La documentation aborde timidement l'interopérabilité technique et opérationnelle entre systèmes et entre les pays, sauf lorsqu'il s'agit des normes ouvertes de l'interopérabilité des capteurs et des données. Cependant, aucun consensus ne dessine à l'heure actuelle au sein de l'industrie quant aux normes à suivre. La mise en œuvre de toute forme de MSE doit reposer sur une sélection rigoureuse des normes, en tenant compte des formats de données et de l'intégration avec les données existantes.

Les incitatifs à adopter la MSE sont les mêmes que les avantages mentionnés : améliorer la sécurité, améliorer les processus opérationnels et de maintenance et réduction des coûts opérationnels et de soutien. En règle générale, les économies sont habituellement calculées à partir de l'évitement des coûts basé sur la réduction des vols d'essai de maintenance, de la durée équivalente de maintenance, du temps d'inactivité des systèmes et de la réduction des coûts de pièces de rechange. La préparation d'une analyse coûts-avantages se transforme en tâche pour comparer les coûts des plateformes avec et sans MSE, et il faut pour cela disposer de données historiques sur les coûts et la maintenance. Parmi les études examinées, toutes à l'exception d'une seule ont relevé des économies substantielles, quelques fois de l'ordre de plusieurs millions de dollars, et un RCI positif. Par contre, ce RCI met parfois des années à se concrétiser et il peut être difficile de justifier l'investissement initial. Les obstacles et les défis que comporte la mise en œuvre de la MSE incluent les coûts élevés d'acquisition et d'installation, l'analyse et l'exactitude des données de pronostic, ainsi que le nombre élevé de fausses alarmes.

Importance : L'étude de données techniques stratégiques commandée devrait permettre aux Forces canadiennes de mieux comprendre les principaux incitatifs et avantages qui favorisent l'adoption de la MSE, ainsi que les grands obstacles et défis à surmonter pour y parvenir, en plus de les aider à mieux exploiter ses ressources pour élaborer une politique ou une stratégie canadienne en matière de SME. Plans futurs : Réaliser une étude pilote analysant en profondeur le rapport coûts-avantages, établir une communauté d'intérêts et entreprendre l'élaboration d'une stratégie en matière de MSE des FC.

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STI Assessment

Product / Title	**Condition Based Maintenance Literature Survey**
Project Numbers	STI 9420, DRDC 13pz18
Prepared for	Dr. Nezih Mrad
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National Research Council Canada
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Canada

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1 BACKGROUND

1.1 Context

Condition Based Maintenance (CBM), also known as “predictive maintenance”, is an emerging maintenance practice that derives maintenance requirements, in large part, from real-time assessment of platform or weapon system condition obtained from embedded sensors and/or external tests and measurements using built-in diagnostic equipment. The goal of CBM is to perform maintenance based only upon the evidence of a need rather than any predetermined time cycle, equipment activity count, or other engineered basis. Capabilities within CBM include enhanced prognosis and diagnosis techniques, failure trend analysis, portable electronic maintenance aids, automatic identification technology (such as Radio Frequency Identification tags) and data-driven interactive maintenance training— a broad range of tools that serve to enhance the maintainer’s ability to support equipment and weapon systems effectively and efficiently.[1] CBM (sometimes referred to as CBM+) may also require business process reengineering to improve logistics system responsiveness.

Autonomic logistics (AL) seeks to automate the data collection function and enable automatic logistics decision making in direct response to the activities of a CBM system. The dynamic range of system activity can impose demand fluctuation on logistics support resources. The goal is to automate sensing of the change in activity far enough in advance to elicit a corresponding adjustive response from the logistics support system. The physiological analogy from which the AL concept is derived is the human autonomic nervous system (ANS).

Condition Based Maintenance is rapidly being adopted by allied militaries, in particular the US, and is an option that appears to offer many benefits over a “time-based” paradigm. DRDC-Atlantic wishes to undertake a project to help determine what potential impact CBM and AL would have on Canadian Forces (CF) operations. The objective is to increase the CF understanding of CBM and potentially develop guidelines to inform stake holders, policy makers and decision makers on:

1. The state of CBM/CBM+ (technology & operation)
2. The linkages between CBM and its variants (e.g. IHM, S&RL, PHM, autonomic logistics, etc.)
3. The benefits of CBM/CBM+ (comparative and gap analysis) – particularly with regards to return on investment (ROI) and potential cost savings
4. Guidelines for developing/implementing CBM/CBM+ (e.g. roadmap)

[1] These definitions are largely derived from the US DoD Defense Acquisition University definitions at: https://acc.dau.mil/cbm

The DRDC project may also involve a case study of CBM-related characteristics, enablers and technologies and their impact on operations including an option analysis comparing "time-based" maintenance versus CBM.
Additionally, the DRDC study will provide:

1. The technological and operational state of autonomic logistics (AL)
2. The benefits of AL (comparative and gap analysis) including ROI and implementation challenges
3. A direction on developing/implementing AL within a military environment (e.g. roadmap)
4. Investigation on the Concept of Operations (CONOPs) used in commercial and military settings (e.g. FedEx, UPS, Walmart) to potentially develop CF/DND Sense &Respond Logistics CONOPs

1.2 Key Issues

DRDC researchers would like to inform the Canadian Forces on the potential of CBM practices to improve military platform performance and provide cost savings. The fundamental questions that should be answered to provide effective guidance to the CF include:

- Should the CF invest in CBM/CBM+ technology development (and/or any of its variants including AL and SRL) and what would be a reasonable expectation for an outcome?
- What should the CF direction be for CBM/CBM+? (e.g. what should we invest in? what kind of roadmap?)

The results of this Strategic Technical Insights (STI) assessment are intended to provide researchers with a solid perspective for their review of the state-of-the-art in this field and to answer specific questions related to Condition Based Maintenance implementation in a military context.

1.3 Key Questions

Questions 1-7 are specific to Condition Based Maintenance (CBM).

1. What are the current and emerging CBM[2] systems/processes/technologies being investigated or implemented worldwide (industry and military)?
2. What are the linkages (conceptual, technological, application-based) between CBM/CBM+ and all of its variants (e.g. IHM, S&RL, PHM, autonomic logistics, CONOPS, etc.)?
3. For which platforms or weapons systems are the CBM systems being used and to what degree of success?

[2] CBM also refers to CBM+ but distinction is made whenever possible.

4. What assessments of CBM implementation have been made discussing Return on Investment (ROI), cost savings or process efficiencies? Has ROI been observed?
5. What are the barriers and drivers to adoption (i.e. policies, processes, organizational, technological, and infrastructure (PPOTI)) of CBM by military and civilian organizations?
6. What are the impacts of CBM/CBM+ on interoperability (i.e., if everyone is using CBM practices can join forces use each other's parts during an operation)?
7. What current policies, strategies, guidance, roadmaps have been issued by military organizations with regards to CBM?
8. Who are the major academic, government and industry players in this domain worldwide? What are their areas of expertise?
9. Who are the leading experts (individuals) in this field worldwide and what are their areas of expertise? Who are the leading Canadian experts and what are their areas of expertise?

Questions 10-13 are specific to Autonomic Logistics and Sense & Respond Logistics in general.

10. What is the current technological and operational state of autonomic logistics (restricted to systems which are connected to maintenance and repair functions, such as CBM)?
11. What are the CONOPs (e.g. processes, technologies, changes or improvements in supply chain management) used in commercial (e.g. FedEx, UPS, Walmart) and military settings that could potentially assist in the development of a CF/DND S&RL CONOPs?
12. What are the benefits/cost savings/efficiencies expected from the implementation of CBM combined with AL (including ROI and implementation challenges)?
13. What are the published lessons learned from the battle field or other implementations of CBM, AL, and SRL in a military setting?

2 INTRODUCTION

In order to provide a framework for this report, a few definitions of key concepts are provided below. There seems to be some variation in common usage of many CBM-related terms and much discussion in the literature about precisely defining those terms and the differences between concepts such as Prognostics and Health Management (PHM), Structural Health Monitoring (SHM), Integrated Vehicle Health Management (IVHM) and so on. To address this, a high level schema of key concepts in CBM is also proposed.

The US Department of Defense (DoD) *Condition Based Maintenance Plus Guidebook* provides the following definitions (Deputy Under Secretary of Defense for Logistics and Materiel Readiness 2008):

CBM is "an established approach to identifying and scheduling maintenance tasks. It employs continuous or periodic assessment of weapon system condition using sensors or external tests and measurements through first-hand observation or portable equipment. The goal of CBM is to perform maintenance only when there is evidence of need" (CBM+ Guidebook, p. 1-3).

CBM+ involves a more proactive and predictive approach than CBM that is driven by condition sensing and integrated, analysis-based decisions:

> With more accurate predictions of impending failures (based on real-time condition data), coupled with more timely and effective repairs, moving toward CBM+ will result in dramatic savings—in time and money—and improved weapon system availability and performance. CBM+ uses modern maintenance tools, technologies, and processes to detect the early indications of a fault or impending failure to allow time for maintenance and supply channels to react and minimize the impact on system operational readiness and life-cycle costs. CBM+ provides a means of optimizing the approach to maintenance, and is a vehicle to reduce scheduled maintenance requirements. The flexibility and optimization of maintenance tasks with CBM+ also reduces requirements for maintenance manpower, facilities, equipment, and other maintenance resources (CBM+ Guidebook, p. 1-3).

Within the CBM domain, there are several terms that are used widely, sometimes interchangeably:

- Prognostics and Health Management (PHM)
- Structural Health Monitoring (SHM)
- Health and Usage Monitoring Systems (HUMS)
- Integrated Vehicle Health Management (IVHM)

From our analysis of the literature, it appears that all of these terms are virtually synonyms, but they differ in terms of the platforms or systems they have evolved from or are usually applied to. Brief definitions of these terms are found below. There are other such terms that are variations on the same words, such as Diagnostics, Prognostics and Health Management (DPHM) or Integrated Health Management (IHM).

Prognostics and Health Management (PHM) has been described as "a health management approach utilizing measurements, models and software to perform incipient fault detection, condition assessment, a failure progression prediction" (Kalgren, Byington et al. 2006). In the context of aircraft maintenance, PHM has been described as the application of technology to predicting parts failures and isolating failed parts. It must anticipate a part failure in time to remove it before it becomes a problem. When a replacement part has been installed, it must check out the system to ensure the corrective action has solved the problem (Byer, Hess et al. 2001).

Structural Health Monitoring (SHM) is "the process of implementing a damage identification strategy for aerospace, civil and mechanical engineering infrastructure" (Farrar and Worden 2007). SHM has come to mean much more than that since the term was first introduced about 30 years ago, as it now also includes aspects of diagnosis, prognosis and decision support. Muravin et al similarly describe SHM as "a process of diagnosis and monitoring the condition of structures normally performed during their operation" (Muravin, Muravin et al. 2010). Their presentation further defines other terms related to SHM, such as diagnosis, prediction, condition monitoring, as well as describing how SHM "combines elements of non-destructive testing, condition/process monitoring, statistical pattern recognition and physical modeling."

Health and Usage Monitoring Systems (HUMS) "were developed over 30 years ago in reaction to concern over the airworthiness of helicopters. The purpose of HUMS is to increase safety and reliability, as well as to reduce operating cost, by providing critical component diagnosis and prognosis…HUMS effort focused on rotorcraft, which benefit from a system's ability to record engine and gearbox performance and provide rotor track and balance" (Mrad and Lejmi-Mrad 2011). While the term HUMS usually refers to monitoring systems for rotorcraft, the more generic term, health and usage monitoring, is also commonly found. As with SHM, HUMS has evolved over the years beyond monitoring and has come to include both diagnostics and prognostics.

Integrated Vehicle Health Management (IVHM) is another term with similar meanings to the above, however it has evolved from work with fixed wing aircraft rather than rotorcraft (Mrad and Lejmi-Mrad 2011). IVHM is also the term usually used by researchers and developers of maintenance systems for ground vehicles. Wheeler et al. noted that similarly to HUMS, the concept of IVHM was introduced about 30 years ago for system monitoring and onboard fault protection as well as failure analysis and modeling (Wheeler, Kurtoglu et al. 2009). Wilmering defines IVHM as "the unified capability of an arbitrarily complex system of systems to accurately assess the current state of the health of member systems, and assess that state of health within the appropriate framework of available resources and operational demand" (Wilmering 2003). The key components of an IVHM system, as defined by Wilmering, are Built-in-Test (BIT) (i.e. embedded diagnostics), diagnostics, prognostics, health monitoring and health management – all components that we see in all other definitions of these common CBM terms.

Figure 1 below provides a schema of the key concepts in the CBM domain.

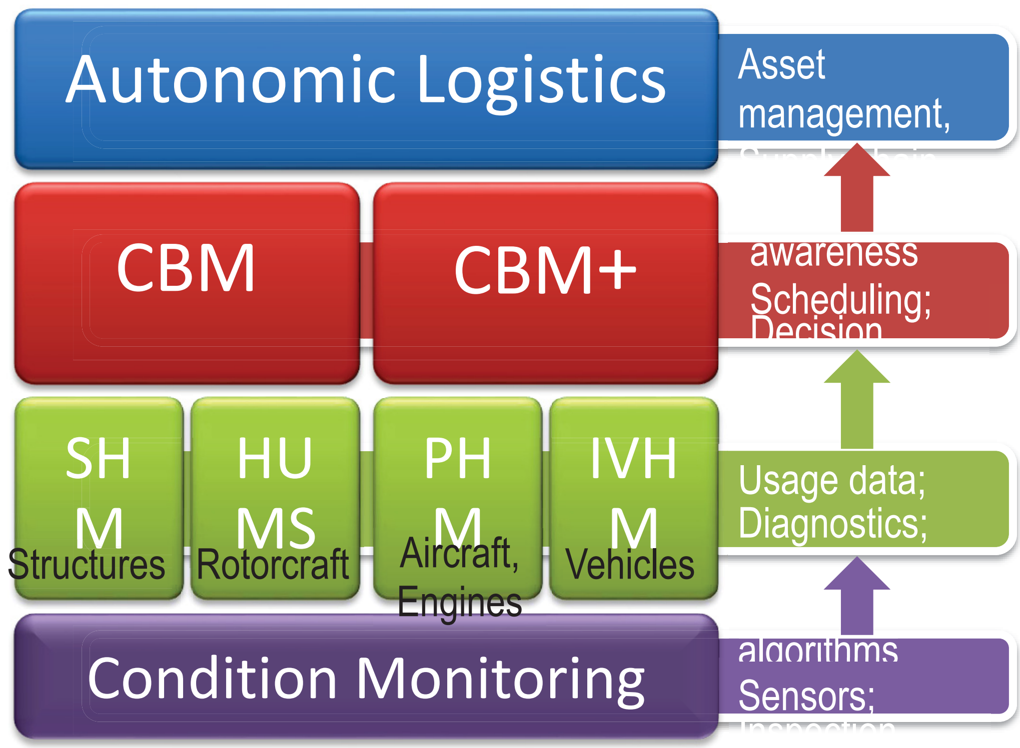

Figure 1. CBM and Autonomic Logistics Concepts

Figure 1 should be read as a hierarchy where condition monitoring forms the base and the boxes above it make up the building blocks for autonomic logistics (AL), found at the top. AL adds an additional dimension to the hierarchy in that it is "the application of automation to locating and ordering repair parts so that they are available when needed" (Byer, Hess et al. 2001). AL systems are very complex and include aspects of asset and supply chain management, logistics and mission situational awareness in the case of military applications. AL will be discussed further in section 6 of this report.

PHM, SHM, HUMS and IVHM are often discussed in terms of being inputs to CBM systems. Figure 1 reflects this assertion in that those concepts are related specifically to diagnosis, prognosis and prediction, while CBM systems contain the decision making and task scheduling components. Where the distinctions may be made among these concepts is in the technologies or activities associated with each of the concepts (shown on the right).

Figure 2 presents an analysis of terms extracted from over 4,000 research publications in the CBM domain and shows the numbers of records in common between key CBM terms and the platforms or systems they are (most commonly) discussed with in the literature. The platforms or systems that are most associated with SHM, HUMS, PHM, and IVHM in Figure 2 have been added to the green boxes in Figure 1.

	Concept				
Platforms & Systems	SHM	PHM	HUMS	IVHM	CBM
Structures	800	59	13	12	70
Aircraft (excl. Rotorcraft)	377	157	46	40	89
Civil structures / Bridges	181	7			9
Engines	98	161	20	30	403
Ground vehicles	85	24	8	53	48
Military applications	81	82	29	13	88
Manufacturing / production	76	40			88
Space applications	68	11		19	7
Rotorcraft	49	30	40	5	48
Remotely operated vehicles	36	9		6	
Electronics	33	76	5	5	29
Naval vessels	35	16			29
Satellites	17				
Machinery	14	36			72
Railway applications	13				15
Weapon systems	11	10			15
Propulsion systems	7	12		5	9

Figure 2. Frequency of Platforms & Systems co-occurring with CBM concepts, number of records

In the chart above, HUMS appears to be more associated with *Aircraft (excluding Rotorcraft)* than with *Rotorcraft*, however, this is likely due to the generic nature of the indexing of the documents. Some indexes likely classify helicopters as simply aircraft. As mentioned earlier, HUMS evolved from research efforts related to rotorcraft.

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3 CONDITION BASED MAINTENANCE TECHNOLOGIES AND SYSTEMS

3.1 Technology Trends

In order to identify technologies discussed in the CBM literature, a comprehensive search in various databases and resources was conducted. A full description of the search strategy is provided in appendix 10.2. A total of 4,394 bibliographic records of journal articles, conference papers, theses and dissertations as well as government technical reports and publications, published between 2006 and 2011, were gathered and uploaded to VantagePoint software[3] for analysis. In addition, records for 1,204 patent families[4] were also gathered and analysed (1990-2011).

Cluster analysis based on the co-occurrence of keywords in bibliographic records is one method of analyzing and visualizing topics that are important in an S&T domain, as well as their relationships to each other. Figure 3 shows a detail of a large cluster map based on the 300 most frequently occurring keywords in the dataset,[5] generated using TouchGraph Navigator[6] software. TouchGraph's clustering algorithm clusters terms together based on statistical similarity to each other (i.e. word co-occurrences) and dissimilarity with other clusters. Generally, a cluster illustrates a self-contained group of concepts that is independent from (though still connected to) the rest of the graph.

The size of the nodes in this map represents the number of publications associated with each node, and the lines in between nodes show the correlation coefficient between two nodes. Only correlations of 20% or greater are shown in this map as well as in all subsequent maps in this report, unless otherwise noted.

In Figure 3, one can see the importance of sensor technologies (such as piezoelectric, fiber Bragg grating sensors, fiber optics and ultrasonics), as well as CBM concepts, types of damage or condition indicators (vibration, cracks), and some condition metrics such as failure diagnosis and remaining useful life (RUL). There is also a significant cluster related to wireless sensor networks and wireless communications. All of these topics will be discussed in subsequent sections of this report.

[3] VantagePoint is produced by the US company Search Technology: http://www.thevantagepoint.com/

[4] Families are groups of substantively equivalent patent applications launched in multiple jurisdictions by the same assignee within a limited period of time, or iterations of an original application. One family essentially represents one invention.

[5] The complete map is provided as an attachment to this report; filename: 9420 CBM Top300 Cluster Map – Figure 3.png

[6] TouchGraph Navigator is produced by the US company TouchGraph LLC: http://www.touchgraph.com/navigator

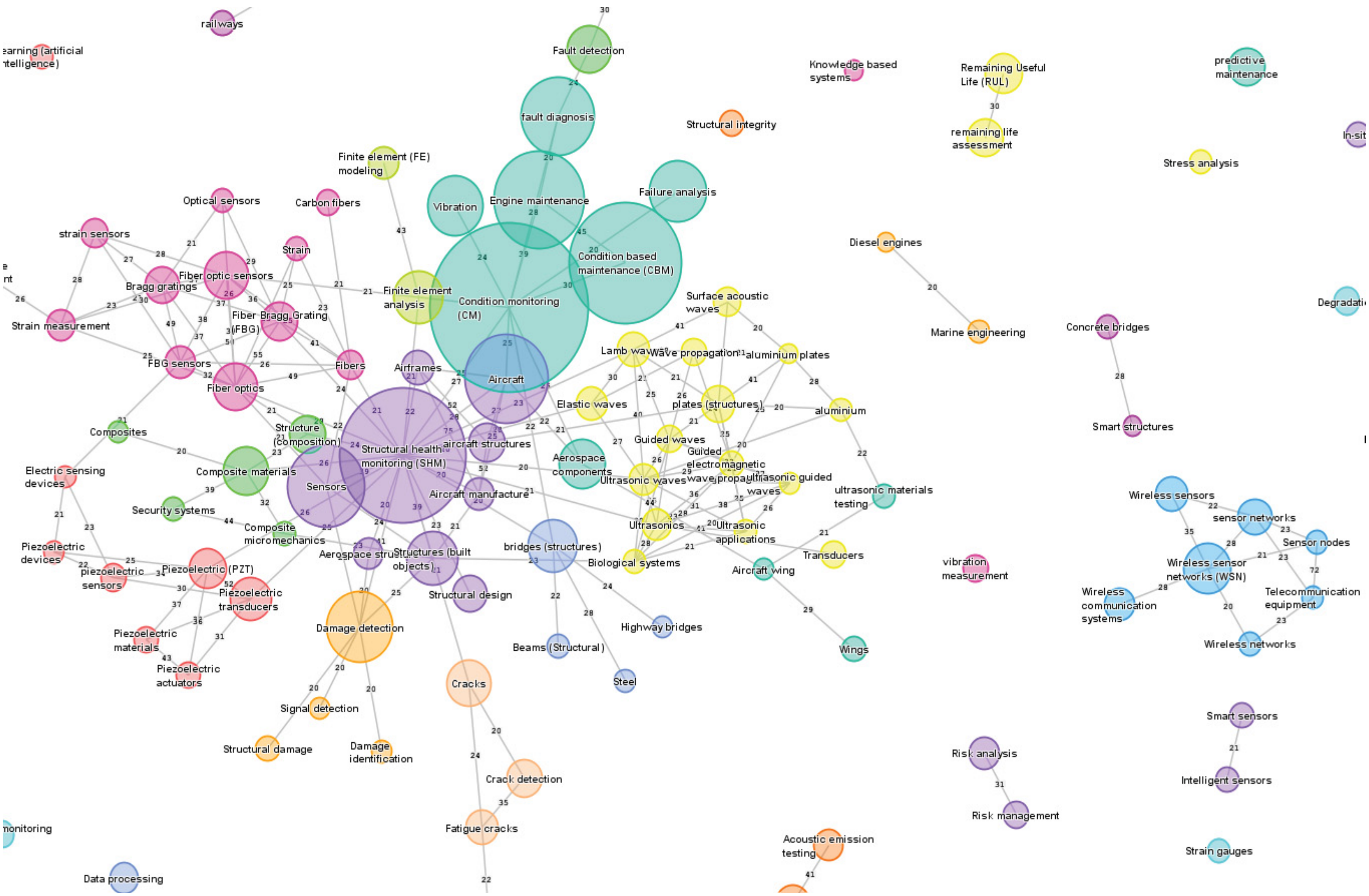

Figure 3. Cluster Map, detail - Top 300 Terms

Using the cluster map as a guide, the top 300 terms and additional, related terms found in the dataset were classified into 90 more comprehensive subject groups. This grouping allows for the identification of the key research topics in the domain. Figure 4 shows the top 20 subject groups in the dataset, based on numbers of publications.

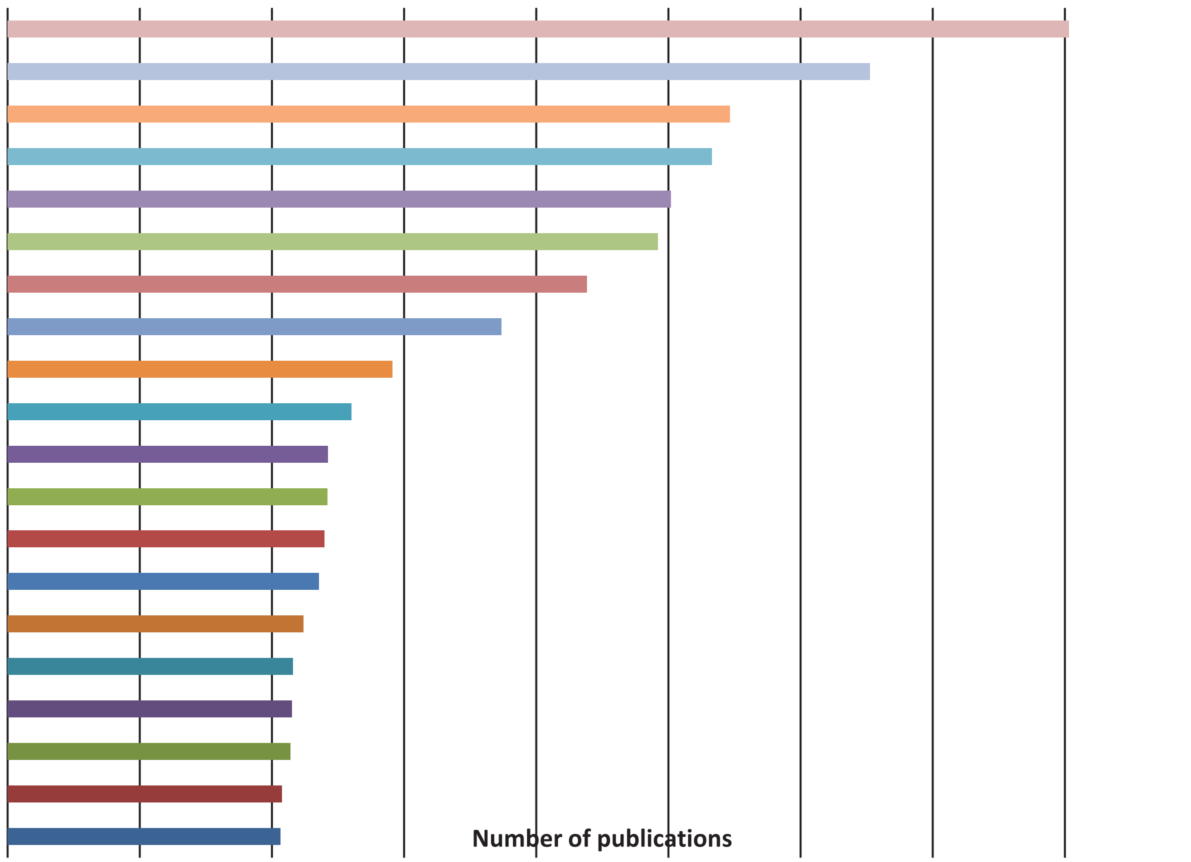

Figure 4. Top Subjects – Literature

Figure 5 below, maps all 90 subject groups that were created and illustrates the relative number of publications for each subject group and the relationships between the different topics, similarly to the cluster map shown in Figure 3. These topics cover a wide range of subjects including basic CBM concepts, types of equipment and platforms to which CBM is applied, sensor technologies, condition indicators and metrics, and other topics, which will be discussed in the sections that follow.

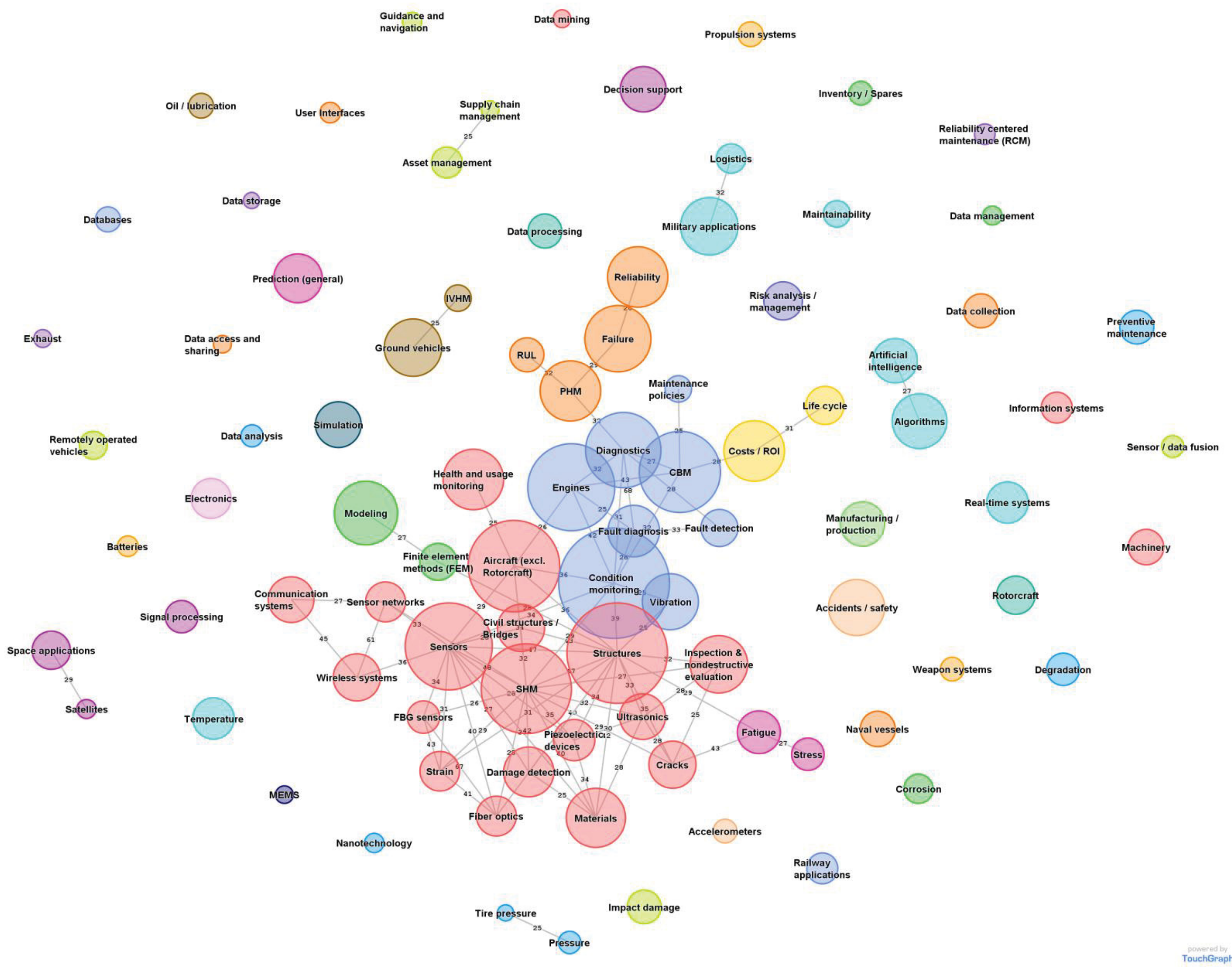

Figure 5. Cluster Map - Subject Groups

The U.S. Department of Defense (DoD) *CBM+ Guidebook* (pp. 3-18 to 3-23), provides a summary of key technologies and processes associated with CBM, as listed below. This outline is very useful in assessing and categorizing the subject groups from our own data, which will be discussed in the sections that follow. The 90 subject groups in Figure 5 were further classified into the categories outlined by the DoD and the relative numbers of publications for each category are shown in Figure 6 below.

- *Sensors* – this category refers to physical devices that are usually positioned on or near the equipment being monitored. These devices could be relatively simple single-function units to multi-purpose testing equipment with some embedded analytical capability.
- *Condition Monitoring* – this process provides the link between the sensor device and the health assessment analysis capability. Condition monitoring includes technologies such as vibration measurement and analysis, infrared thermography, oil analysis and tribology, and ultrasonics.
- *Health Assessment* – involves the capability to use the inputs from condition monitoring of system behaviour and to provide an assessment of the equipment's operational condition. DoD defines these as "on-system" or "at-system", which is different from *Analytics*, described below.
- *Analytics* – this term refers to health management analysis software whose primary function is to "determine the current health state of equipment and project this assessment into the future, taking into account estimates of future usage profiles" (p. 3-21). The different functions of this software may include: condition monitoring, fault diagnosis, predictive assessment, trend analysis and prognostic assessment (i.e. measures of remaining useful life (RUL)). Analytic software usually operates off-system rather than on-system.
- *Communications* – this category includes the transmission of condition-related data, other technical information, technical descriptive data, maintenance procedures and management information.
- *Data management* – this area includes data acquisition, data storage, accessing data, etc. Data are usually held in two ways: on-system in small amounts to support embedded health assessment and reporting, and off-system in a larger electronic storage media.
- *Decision support* – these tools acquire data from the diagnostics and prognostic analytics to help managers at all levels identify adverse trends and assist in maintenance planning. Decision support may also include the use of data by other players or systems, such as supply, transportation and engineering.
- *Human interfaces* – the human interface capability provides a means for operators to input condition information into the health management system, but also to provide multiple layers of access to data across the CBM environment, depending on the information needs of the user.

An examination of the subjects found in the literature gathered for this project shows a high degree of interest in all of these aspects, except human interfaces, which is not prominent in our dataset. As well, it is hard within this data to differentiate between *Health Assessment* and *Analytics* as understood by the DoD. Nevertheless, this framework was used as a basis for the categorization of the literature and the discussions that follow.

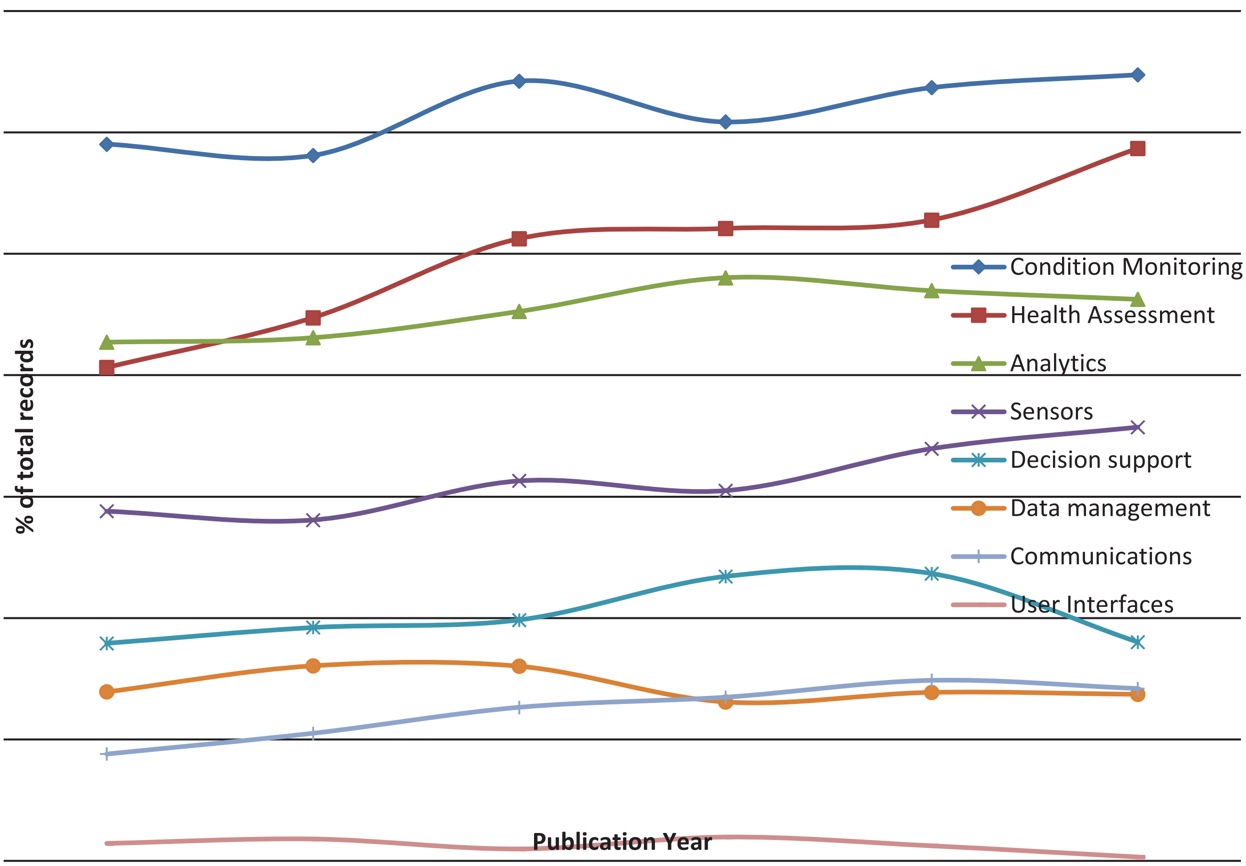

Figure 6. CBM Hardware and Software Technologies, % of total records

Figure 6 uses the DoD classifications and shows the relative coverage of those eight topic areas in the literature dataset. The areas of primary interest for this study are condition monitoring, sensors, health assessment, analytics, communications and decision support and each will be treated in detail below. Data management and user interfaces are of lesser importance and have been excluded from our discussions.[7]

[7] NRC-CISTI has produced two other reports on data management (Keating 2010) and common operational picture systems (Brady and Keating 2011), which may be useful for further information on these topics.

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3.1.1 Sensors

The following section discusses sensor devices and trends in sensor development for CBM. In order to provide details on sensor technologies, a subset of the literature dataset was created containing all the articles that specifically mention sensors or sensor networks. The sensor subset comprises 1,373 records and represents 31% (1,373/4,394) of the total dataset.

According to a 2008 Frost & Sullivan publication, the following are the current trends in sensors for aerospace and defence applications (Frost & Sullivan 2008):

- PHM is a key driver for sensor development.
- Nanosensors and nanomaterials are gaining increased focus.
- Fibre optic sensors' light weight makes them ideally suited for health monitoring in vehicles.
- Increased need for sensor networks operating in hostile environments – to compensate for sensor failure.
- Sensor data fusion is a key enabler.
- Interoperability could be an issue – there is a possibility of incompatibility among sensors deployed and therefore a need for standards for sensor technology and data analysis.
- Low-power requirements and energy harvesting important for operations over the long term.

All of these topics are seen in the references gathered for this project, and will be discussed below.

Figure 7 below is a detail of a cluster map of the top 300 terms in the sensors subset.[8] This figure provides a more granular view of the topics of importance for sensors in CBM than was seen in Figure 3. The largest cluster, in the center in red, is primarily concerned with damage detection for both aircraft and structures – the primary sensing technologies associated with damage detection are ultrasonics and piezoelectric devices. To the right, in blue, is a large cluster related to fibre optics and Fibre Bragg gratings sensors – in this cluster, the primary application of these types of sensors appears to be strain measurement. To the far left, in purple, there is a small cluster related to acoustic emissions sensors, which is most strongly correlated with fatigue measurements.

[8] The complete map is provided as an attachment to this report; filename: 9420 CBM Sensors Top300 Cluster Map – Figure 7.png

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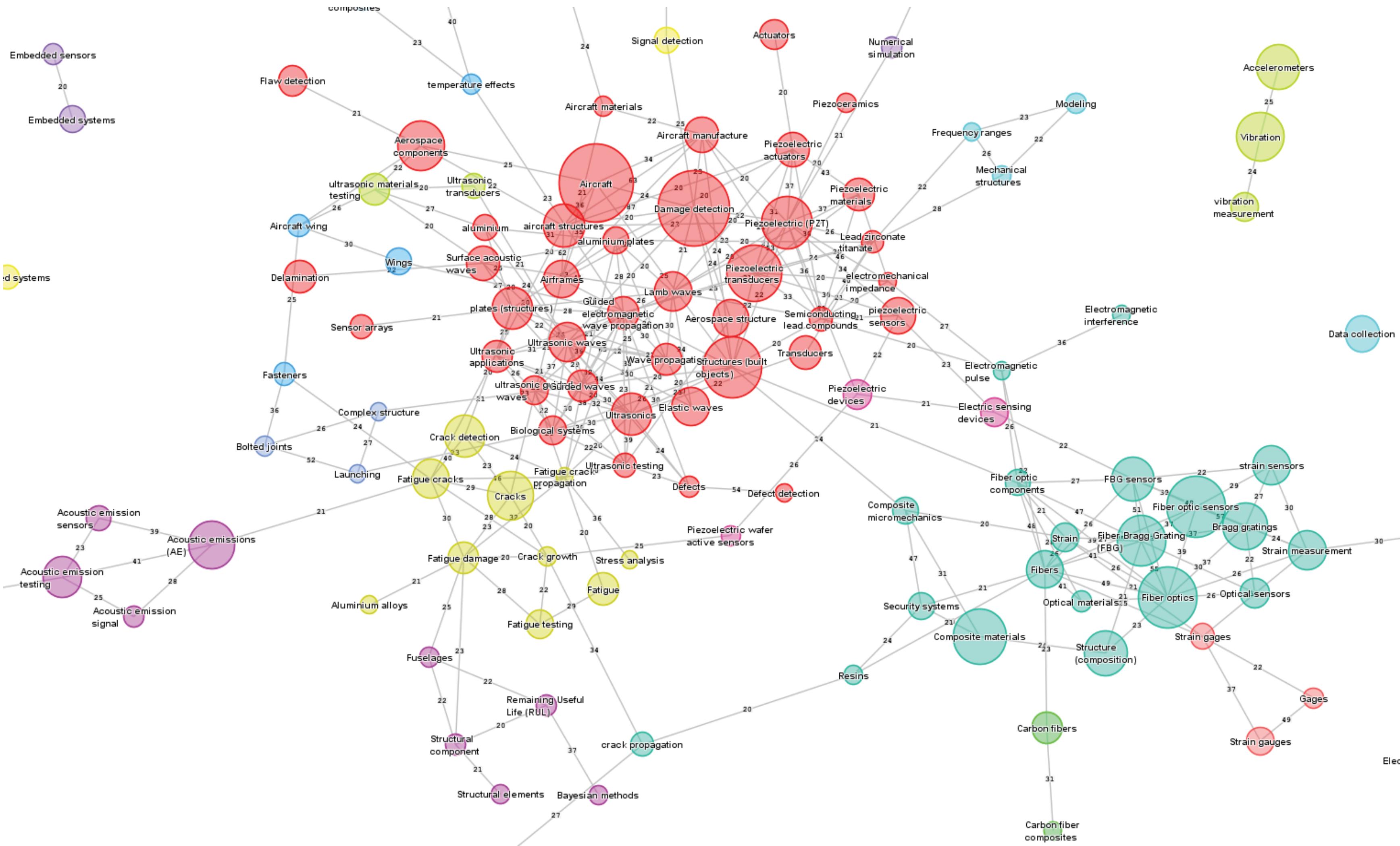

Figure 7. Cluster Map, detail - Sensors Subset

Figure 8 shows the top 20 subject groups in the sensors subset, based on numbers of publications. Many of these groups are identical to those found in the master dataset and shown in Figure 4, however many groups were deleted as they were not of particular interest to the sensors subset. Similarly, many new groups were created, particularly in the areas of sensor materials (for example: composite materials, ceramics, and polymers) and types of waves related to ultrasonics (e.g.: lamb waves, elastic waves). These smaller groups are not found in Figure 8 below, but they can be seen in the cluster map of all the subject groups for the sensors subset (Figure 9).

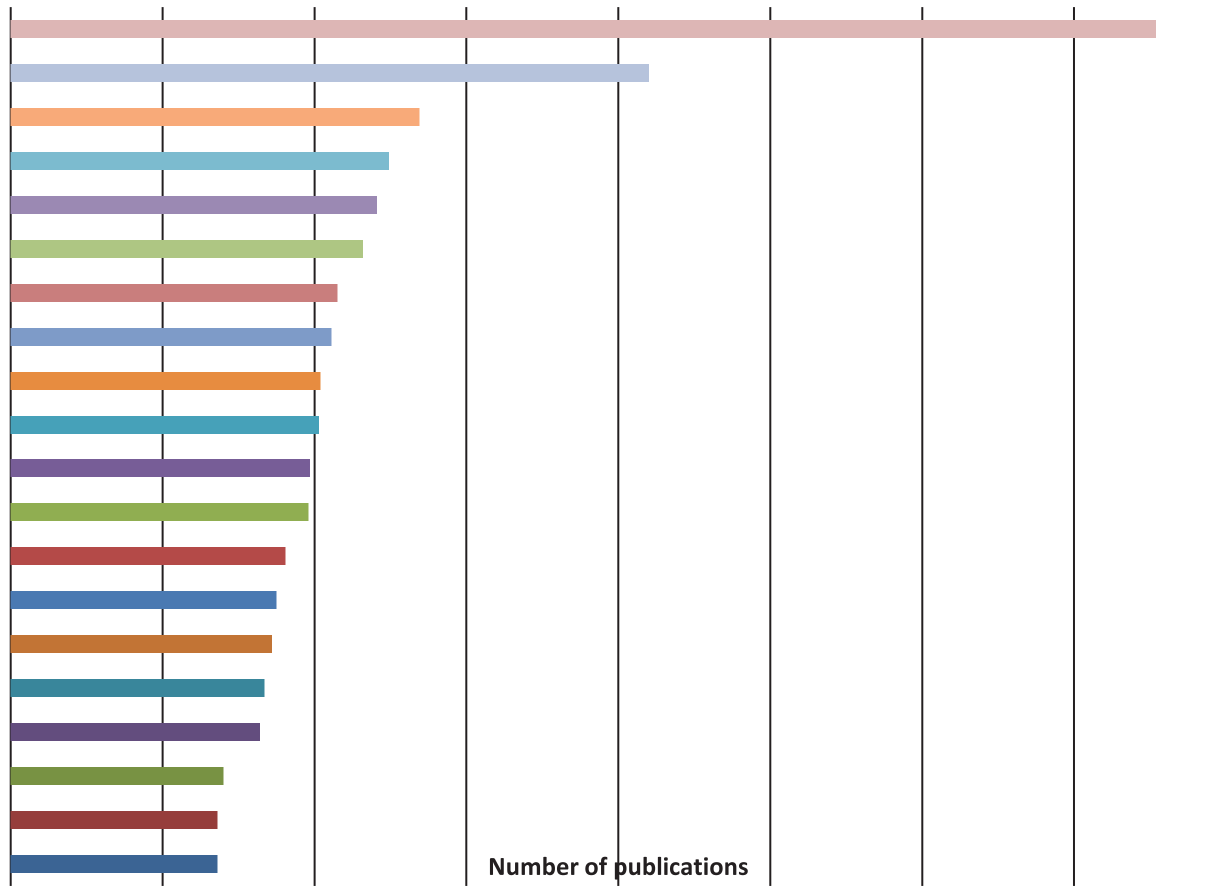

Figure 8. Top 20 Subject Groups - Sensors Subset

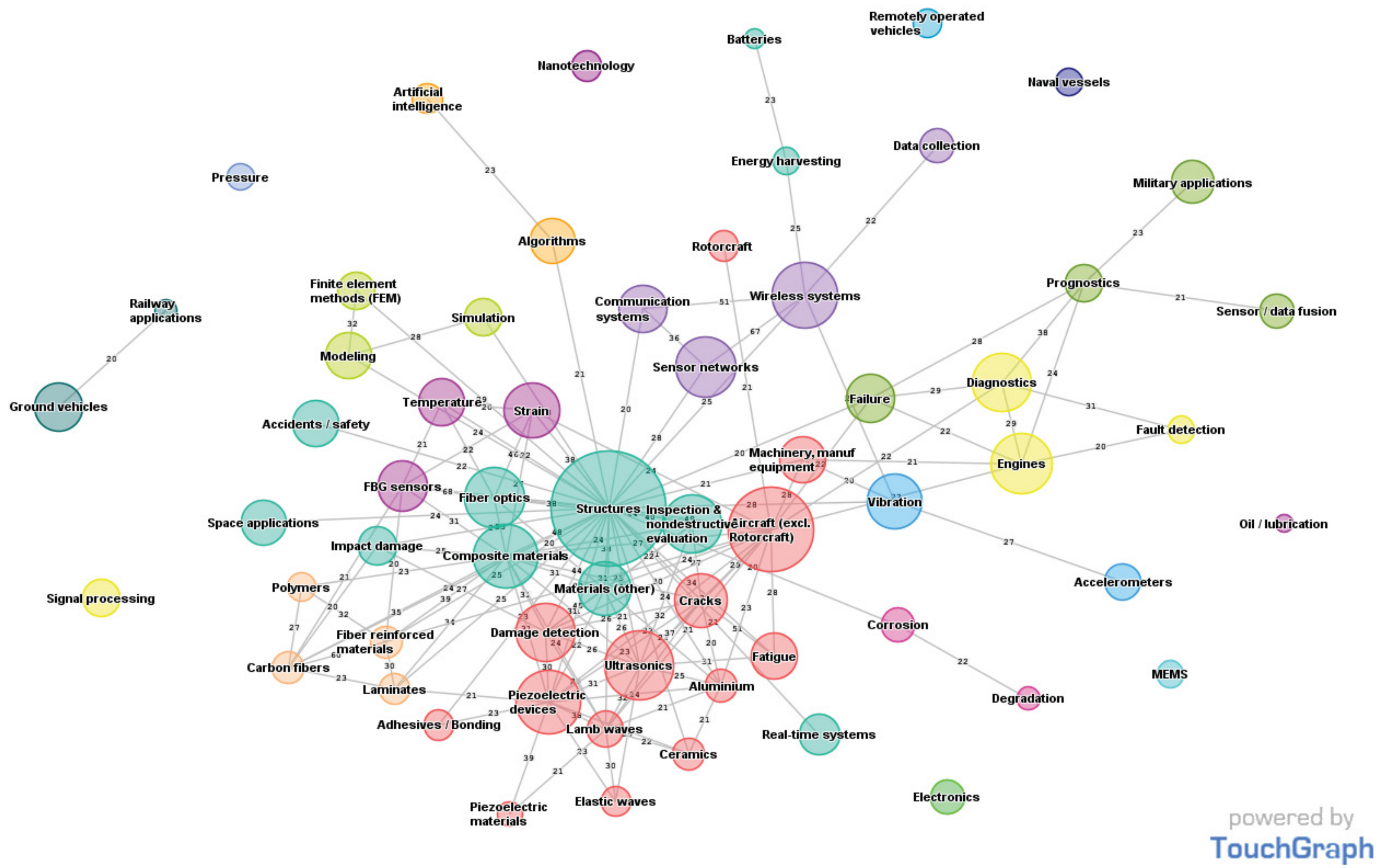

Figure 9. Cluster Map, Subject Groups - Sensors Subset

In order to provide a measure of which subject areas are showing an increasing rate of growth in the domain, an analysis of growth rates using z-score normalization[9] was performed on a sub-group of sensor technologies in general, as shown in Figure 10.

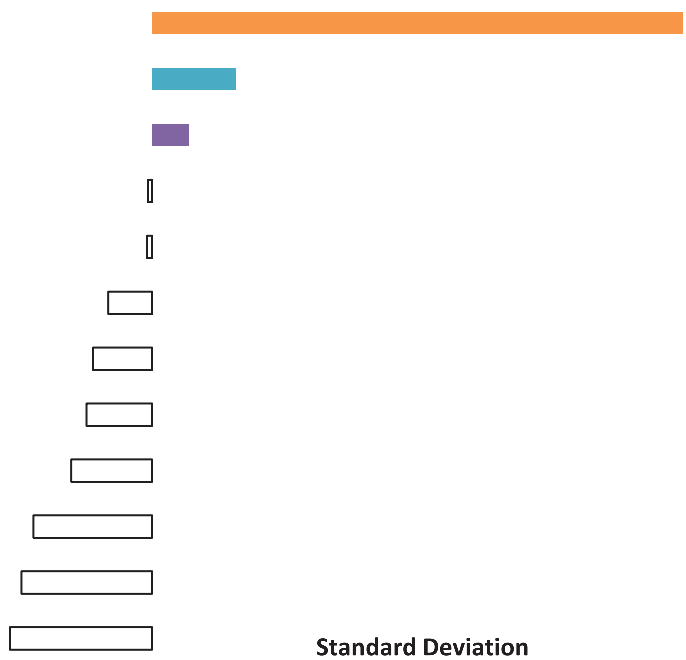

Figure 10. Relative Level of Research Interest - Sensor Technologies

Figure 10 shows that *nanotechnologies*, *MEMS* and *energy harvesting* are the three topics showing the most marked and increasing attention in recent years, which can thus be interpreted as important emerging trends. This measure is not to say that there is decreasing interest in the other topics, only that research on these three are growing the fastest.

MEMS sensors are seen by Frost & Sullivan as an important emerging trend in predictive maintenance (PdM) systems, although more research is needed to improve their performance (Frost & Sullivan 2011). The advantages of MEMS sensors are that they are reliable and have improved the portability of monitoring systems because of their small size. Frost & Sullivan also believe that “opportunities in detector devices for PdM lie with R&D, manufacture, and implementation of piezoelectric MEMS sensors that combine the high performance of piezoelectric technology with the compactness and reliability advantages of MEMS technology” (Frost & Sullivan 2011, 54).

[9] This methodology is described in Appendix 10.2.2.

Closely related to MEMS sensors are advances in nanosensors and nanomaterials. The advantages of small size are particularly attractive for aircraft applications where low weight is required. Frost & Sullivan wrote in 2008 that "Nanotechnology holds tremendous potential and is one of the key technologies that is likely to dominate the aerospace sector. Researchers are exploring the benefits of MEMS and nanotechnology for development of devices based on these smart materials and sensors, leveraging advantages such as reduced size, complexity, and cost" (Frost & Sullivan 2008, 9). The upswing of nanotechnology in the sensors dataset reflects this research interest.

Energy harvesting showed a significant leap in the numbers of publications in 2008 – from only three and two publications in 2006 and 2007 respectively, to ten publications in 2008 and nine in each subsequent year. This activity seems to correspond to Frost & Sullivan's assertion that energy harvesting is another important trend for sensor technology.

In Figure 10, sensor networks or sensor data fusion are not showing any more increase in interest than the other sensor topics, but that could be the nature of the subset. When examined in a subset of the data in which only records about communications technologies and data transmission were retained, the results are somewhat different (see section 3.1.4 below).

3.1.2 Condition Monitoring

Condition monitoring forms the basis for effective CBM and is the link between the sensor device and the health assessment capability. It usually involves sensor devices, but may also include inspections and non-destructive evaluations, which are input by operators into the monitoring system. Figure 11 provides a view of which conditions are most discussed in the research literature. From this graph, one can see that vibration is the most frequently discussed condition indicator over the past six years, and interest in this topic is continuing to rise. Cracks and temperature sensing are the second and third most discussed condition indicators, but growth in interest in these topics are relatively flat when compared to vibration. According to Frost & Sullivan, the predominance of vibration monitoring techniques is due to the reliability of vibration measurements over others (Frost & Sullivan 2011, 23).

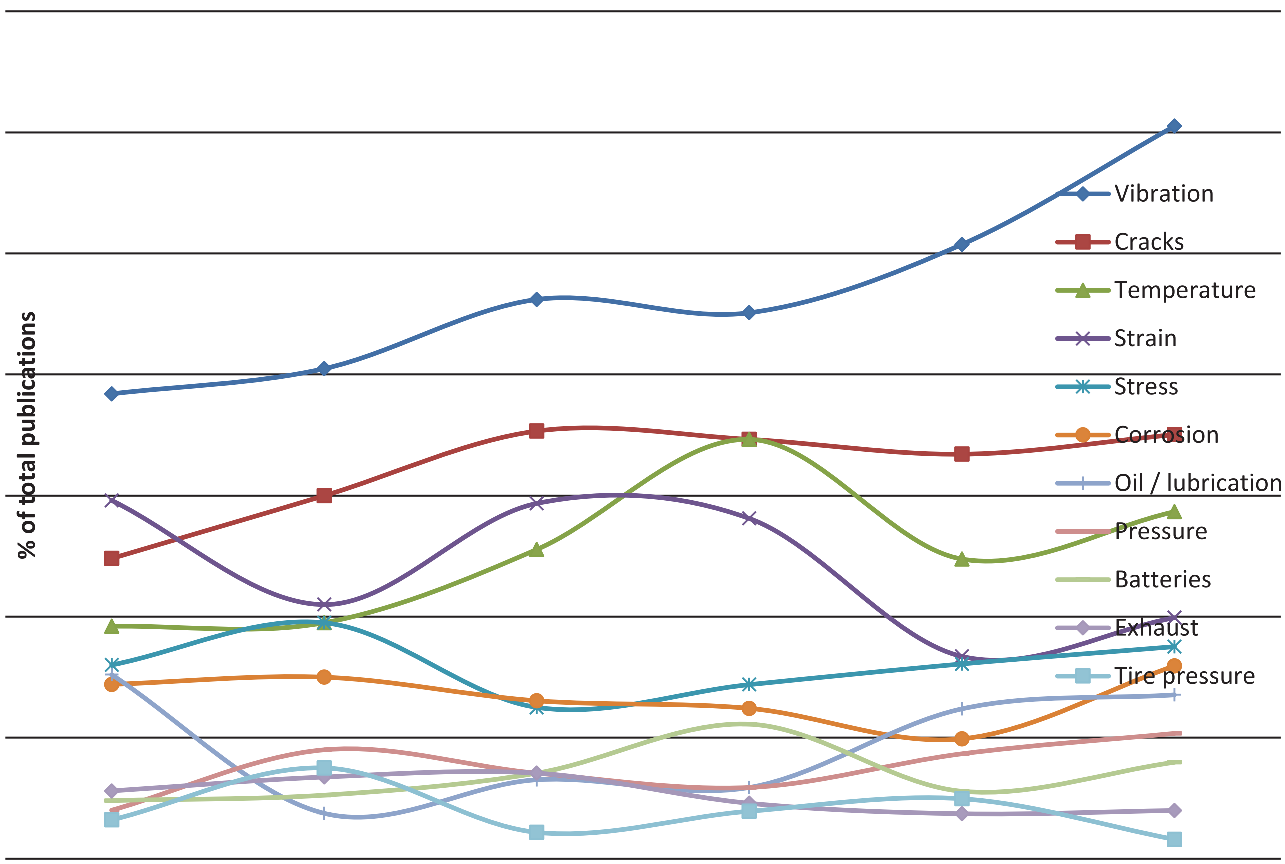

Figure 11. Condition Indicators, % of Total Publications

Figure 12 below shows the number of records for each condition indicator and the sensor types they are associated with in the dataset.

Condition Indicators	Fiber optics	FBG sensors	Ultrasonics	Piezoelectric devices	Accelerometers	MEMS	Nanotechnology
Strain	90	75	18	19	10	4	6
Cracks	23	15	79	46	4	2	8
Vibration	23	14	25	35	32	9	3
Temperature	37	28	18	24	6	3	5
Corrosion	8	3	22	14		6	7
Stress	13	8	18	10	2		4
Pressure	13	8	5	2	2	5	
Batteries			3	3	2		
Oil / lubrication			4		2		
Tire pressure			2			2	

Figure 12. Co-occurrences of Condition Indicators and Sensor Types (numbers of publications)

Figure 12 provides some insight into the types of sensors that are most associated with the types of measurements. For example, strain measurement is most associated with fibre optics and FBG sensors while vibration measurements are most associated with piezoelectric sensors and crack detection are most associated with ultrasonics. This table can be helpful to assess which sensor technologies to consider for a CBM project. Further insights on sensor technologies matched to measurements can be found in (Industry Canada 2004) and (NATO AVT-144 Technical Team 2011).

3.1.3 Health Assessment and Analytics

While the DoD *CBM+ Guidebook* makes a distinction between *health assessment* and *analytics*, depending on if the systems are on-system or if the data is processed elsewhere, this distinction was difficult to make based on an analysis of keywords appearing in the bibliographic records, therefore they are discussed together in this report. These tools include software and algorithms that make diagnostic and prognostic health assessment of system equipment. According to Frost & Sullivan, recent research efforts are concentrated on the software front (Frost & Sullivan 2011).

Figure 13 shows the publication curves for topics related to condition metrics, in other words, the results of the analytical processes, which are measures of system condition used as inputs to decision support tools. In this figure one can see that failure and reliability are receiving the highest degree of treatment in the literature, while the rest are discussed somewhat less so.

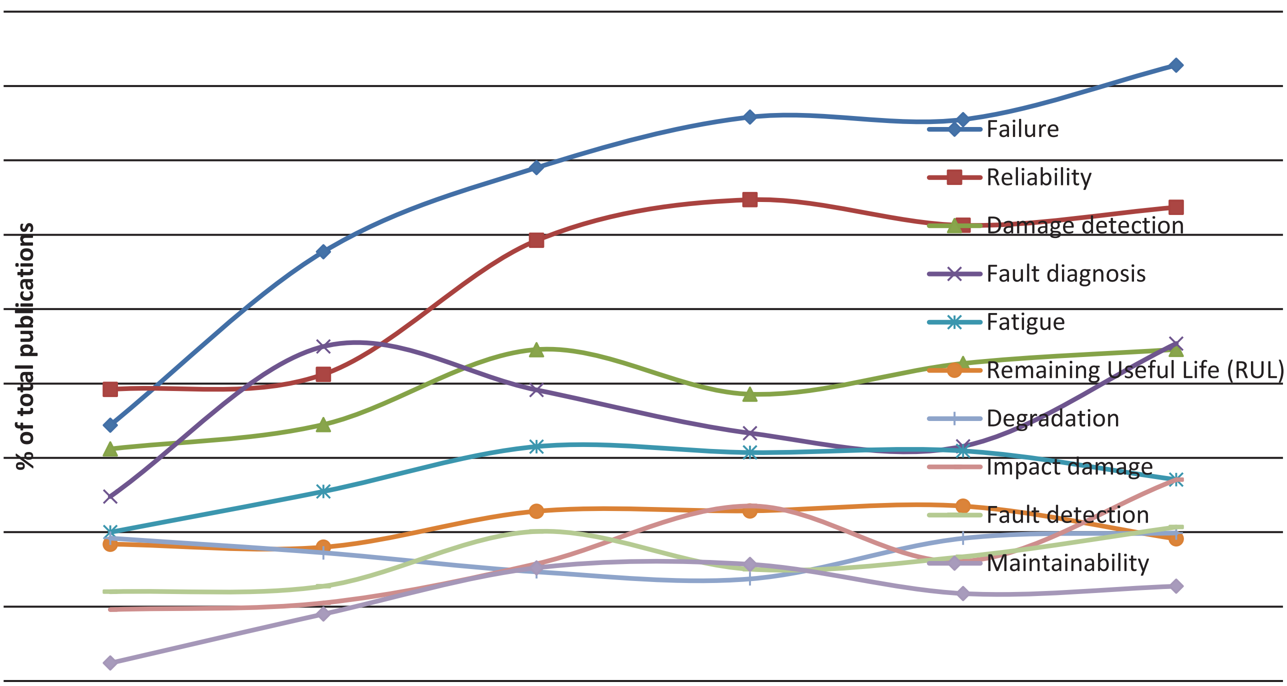

Figure 13. Condition Metrics, % of Total Publications

To further explore the analytical methods for modeling and for determining the condition metrics, such as those found in Figure 13, a subset of the data related to modeling, simulation and analytics was created. The analytics subjects make up a significant portion of the literature in this domain, at about 27% (1,223/4,394) of the entire dataset. A complete discussion of the prognostics methods is not possible within this mandate; however a few trends are visible through a bibliometric analysis of the publications.

Figure 14 shows the key methods related to modeling, simulation and prediction as found in the analytics subset.

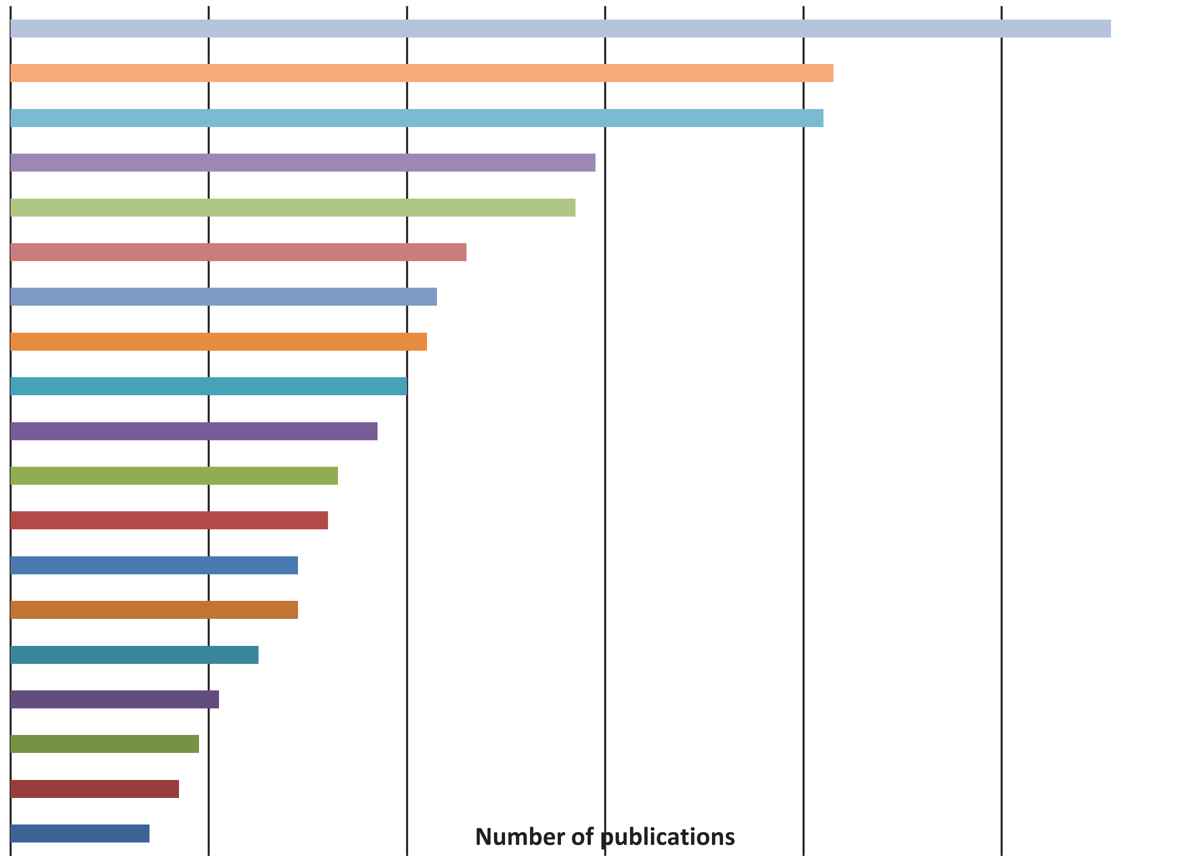

Figure 14. Key Subjects for Modeling, Simulation and Prediction

Of these topics, the methods receiving increasing[10] attention in recent years are:

- Finite element methods (FEM)
- Bayesian methods
- Hidden Markov methods
- Physics-of-failure models

The first three methods above are well-known techniques that are used in many domains but the physics-of-failure models, sometimes referred to as physics-based models, are particular to PHM and use “mathematical equations that theoretically predict the system behaviour by simulating the actual physical processes that govern the system response”(Farrar 2005). It is reported in the literature that physics-based models have received strong interest for failure modeling of mechanical and structural components, as well as electronic equipment (NATO AVT-144 Technical Team 2011, see pp. 6.9-6.10).

[10] A z-score analysis was performed on these groups, but it is not shown here.

3.1.4 Communications Technologies

Following the DoD *CBM+ Guidebook*, communications technologies include anything related to data transmission and communication networks, which in this dataset primarily refers to wireless sensor networks, computer networks and information systems. According to Byer, Hess et al., distributed information systems (DIS) are a critical element of CBM systems for collecting and analyzing data and disseminating the information to decision support systems and AL systems (Byer, Hess et al. 2001). They also discuss the importance of wireless systems for gathering field data and for transmitting aircraft performance data in-flight. The electronic availability of maintenance manuals is also a requirement of the DIS.

To facilitate analysis of the subject area, a subset of the data containing only those papers explicitly related to communications technologies, including those mentioned above, was created, with 582 records, representing 13% (582/4,394) of the master dataset.

Figure 15 shows the top 20 subject groups in the communications dataset. In this graph one can see the importance of wireless sensor networks, wireless systems in general, mobility and portability, and issues related to data collection, processing and transmission.

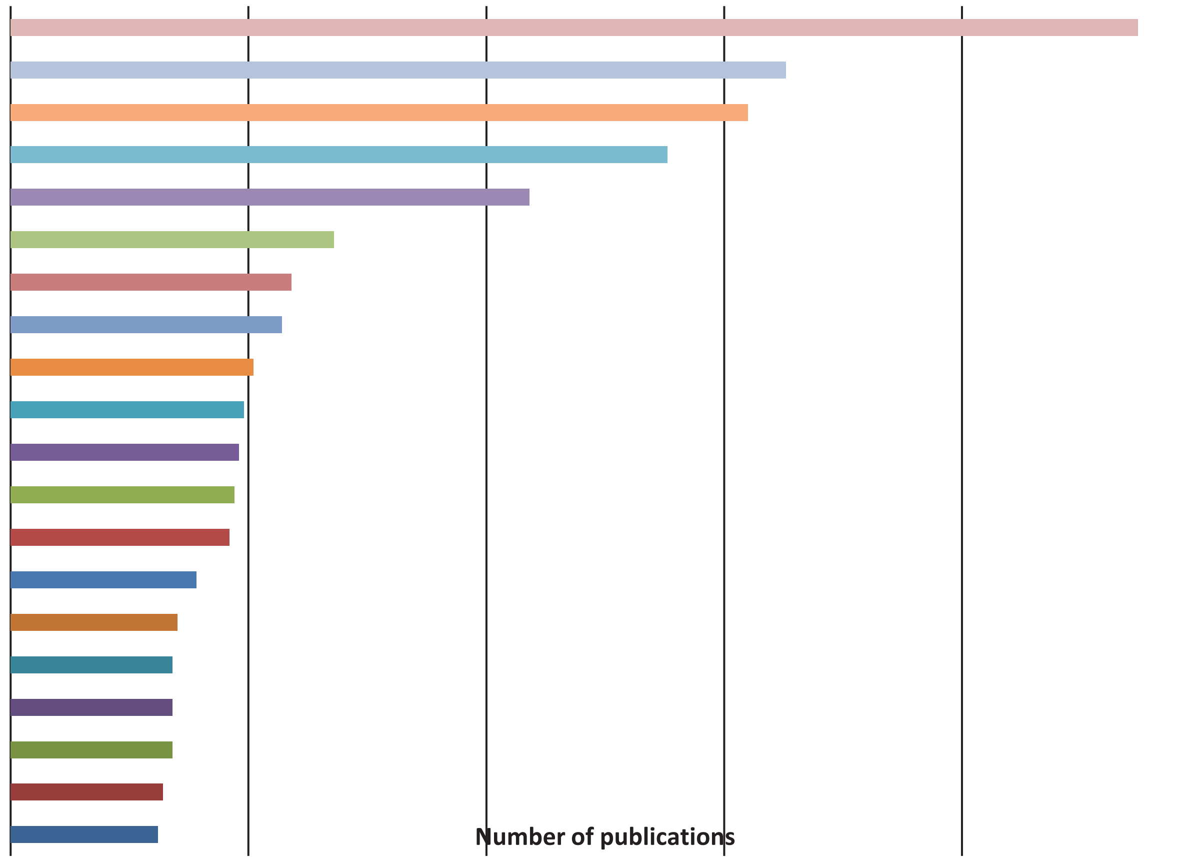

Figure 15. Top subject groups - Communications Subset

In Figure 15, the importance of wireless sensors, sensor networks and wireless systems in general are made evident by the significant number of publications for all of these subjects and their appearance in the top six topics in the entire communications dataset.

Figure 16 illustrates the 35 subject groups created for the communications subset and their relationships to each other. A few important clusters of topics are evident, such as: sensors, wireless sensor networks and wireless systems, in red; topics related to data collection, analysis, transmission and sharing in blue; and other information systems and data processing and analysis topics on the periphery.

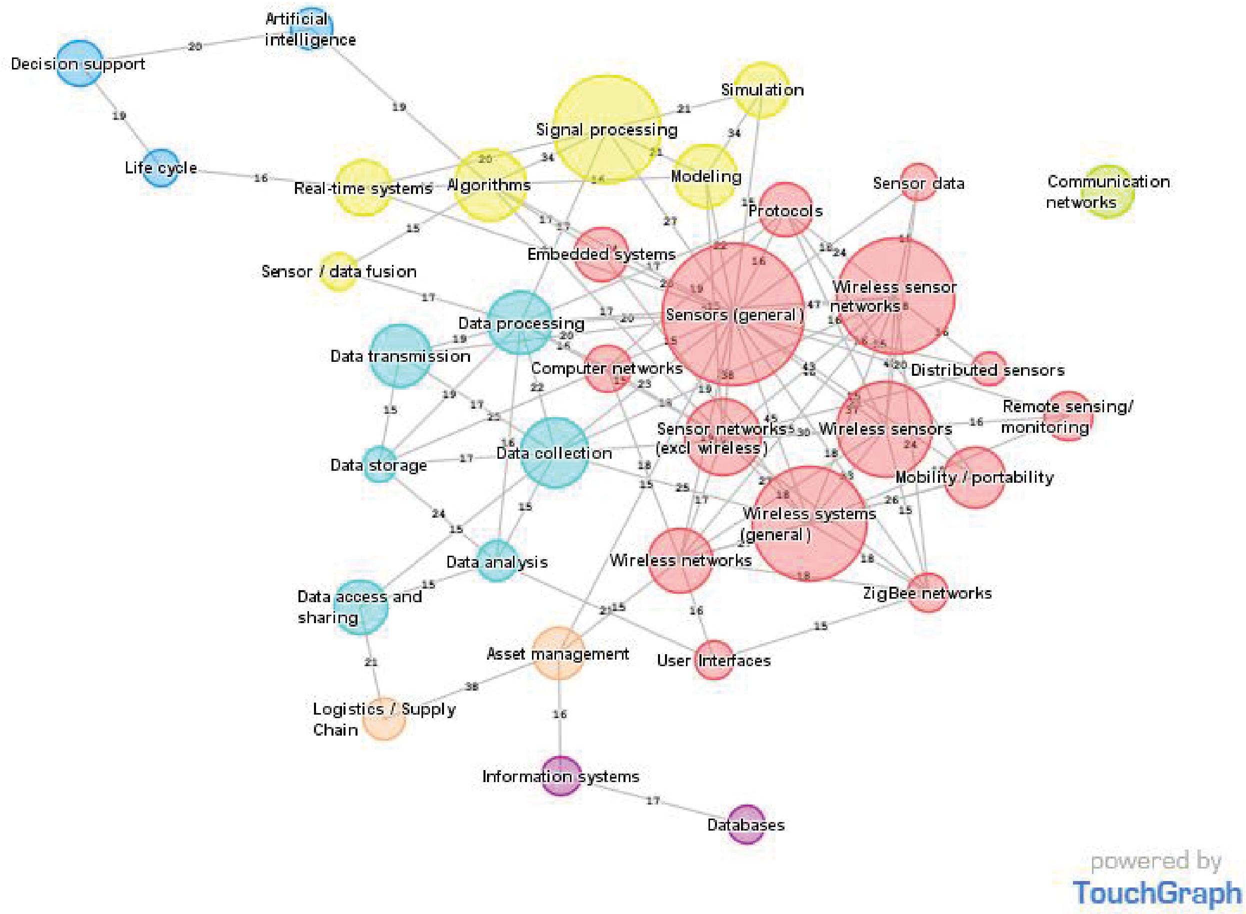

Figure 16. Cluster Map - Communications Subset - Subject Groups

According to Frost & Sullivan, telecommunication networks and short-range wireless communication technologies, such as Bluetooth and Zigbee, are key enablers of predictive maintenance, particularly because of the increased use of real-time monitoring (Frost & Sullivan 2007). Zigbee is typically used in factory settings where multiple pieces of equipment are monitored and the data is transmitted wirelessly to a local server for analysis.

Eleven subtopics related to networking and wireless systems from the communications subset were extracted and plotted using the z-scores method.[11] Figure 17 shows which topics have increasingly attracted research interest over the past six years. Though there are relatively few papers (20) on

[11] The methodology is described in Appendix 10.2.2.

Zigbee networks in the dataset, the recent uptake in interest puts them in the positive scale for relative research interest. Other network technologies and protocols are also seeing increasing interest.

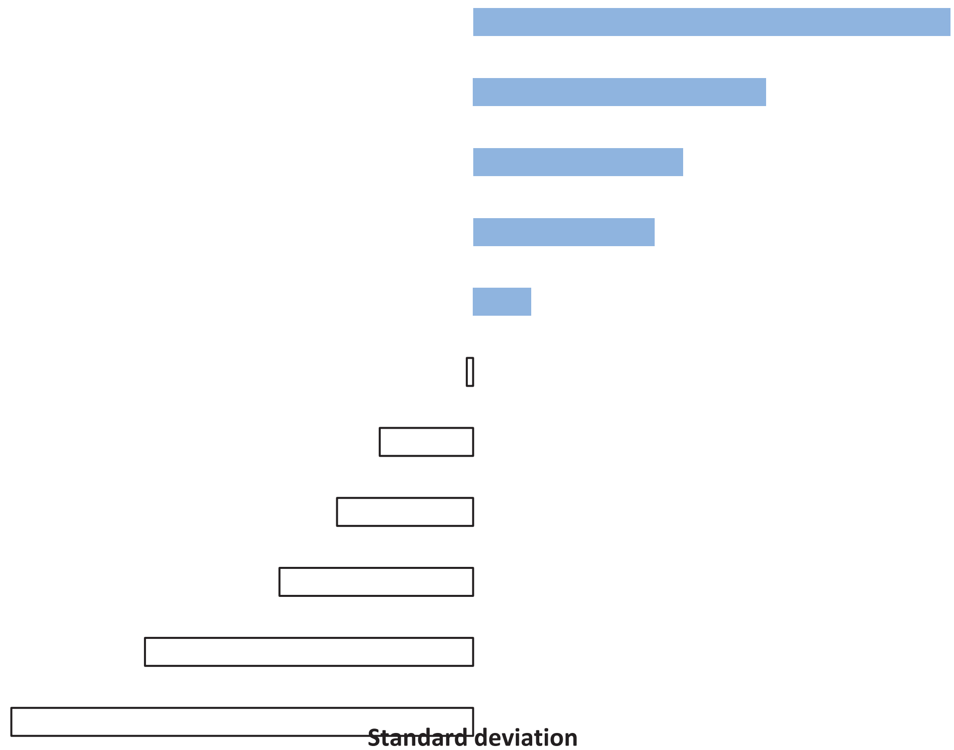

Figure 17. Relative Level of Research Interest - Communications Technologies

3.1.5 Decision Support

Decision support systems and concepts make up a small portion of the master dataset with only 270 records associated with this topic. However, interest in this topic is gradually rising based on numbers of publications over the six year period. It could be that decision support systems are not treated in great detail by the CBM community because the topic crosses over with other domains, such as research into user interfaces and systems for a military common operational picture.[12] Nevertheless, decision support is important in this field as it is specifically related to the purpose of CBM systems – to make effective maintenance management decisions.

In order to explore the topic of decision support further, a subset of the data containing all records related to decision support and risk management was created, containing 438 records and representing about 10% (438/4394) of the master dataset.

[12] See the NRC-CISTI report (Brady and Keating 2011)

The original 90 subject groups were reduced to 33 groups in this subset – in some cases, groups that were small were merged (such as *data management* and *data access and storage*), and groups that were relatively large were split (for example, *risk* was split into three groups: *risk analysis*, *risk management* and *risk (general)*). One new group was also created: *Knowledge-based systems and KM*.

Figure 18 illustrates the top 20 subject groups in the decision support subset. One can see that topics related to risk, reliability, and safety feature prominently in this dataset. As well, there is a high incidence of military-related topics, not seen to this degree in the other subsets. Topics related to life cycle management, asset management and logistics are also important for decision support. The appearance of these topics in the decision support subset illustrates the link between health assessment and analytics to decision making and autonomic logistics.

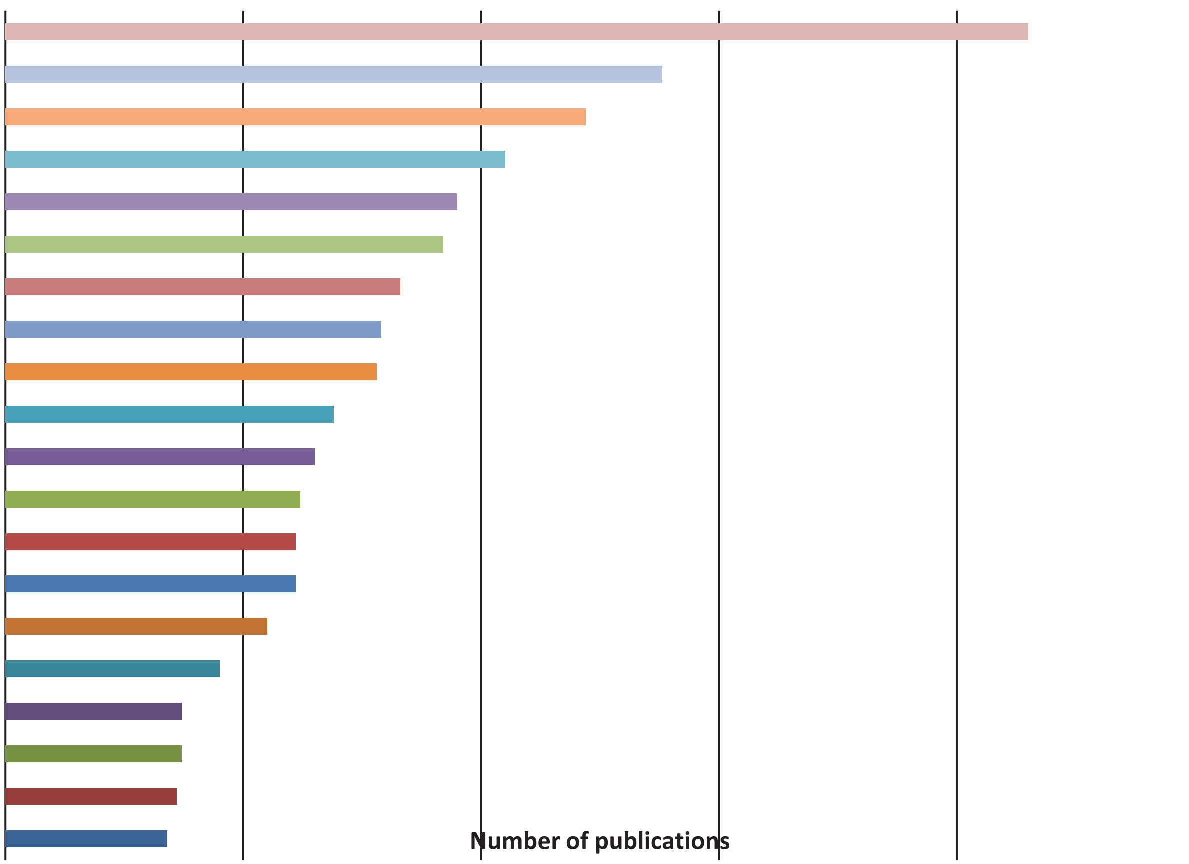

Figure 18. Top 20 Subject Groups - Decision Support Subset

Figure 19 shows a cluster map of the 33 groups in the decision support and risk subset. In this graph the relationship between decision support systems, algorithms and artificial intelligence are evident (in turquoise at top). There is also a significant cluster related to risk and safety/accidents (light orange, bottom right). Topics related to data management and processing (dark orange), linked to information systems and knowledge-based systems (in purple) are found on the left. Finally, in yellow, the importance of logistics-based topics to decision support is represented. These groupings all illustrate the focus on software tools, expert systems and data management for decision support systems as they relate to maintenance and autonomic logistics.

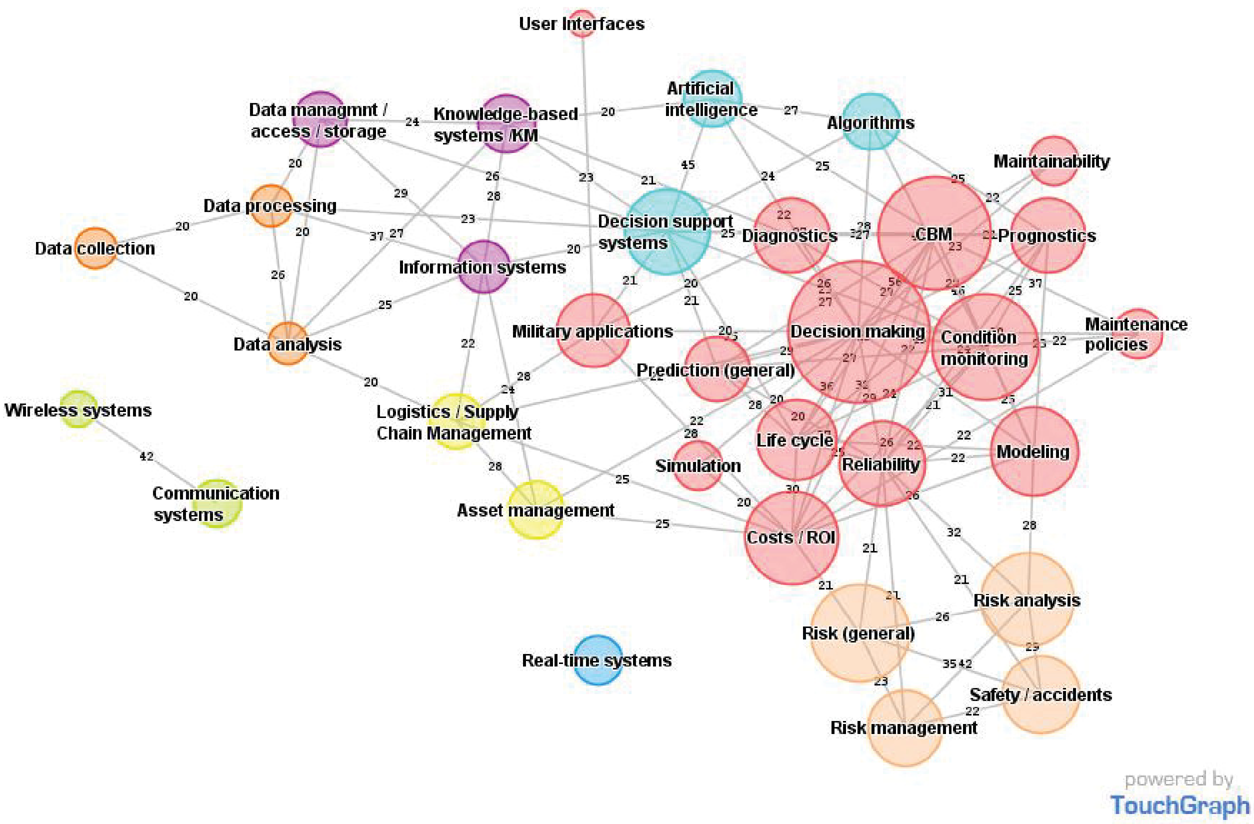

Figure 19. Cluster Map - Decision Support and Risk Subset

3.2 Patent Analysis

Records from 1,204 patent families were compiled and analysed in a similar fashion to the literature analyses described in the sections above. Figure 20 shows an analysis of the patent subject matter, however, these subject groups are based upon International Patent Classifications (IPC) and not on words in the patents. The language of patents tends to be very different from usual published literature and so text-based analysis is not always effective. IPCs are used by patent examiners to classify technologies and the uses for technologies described in the patents.

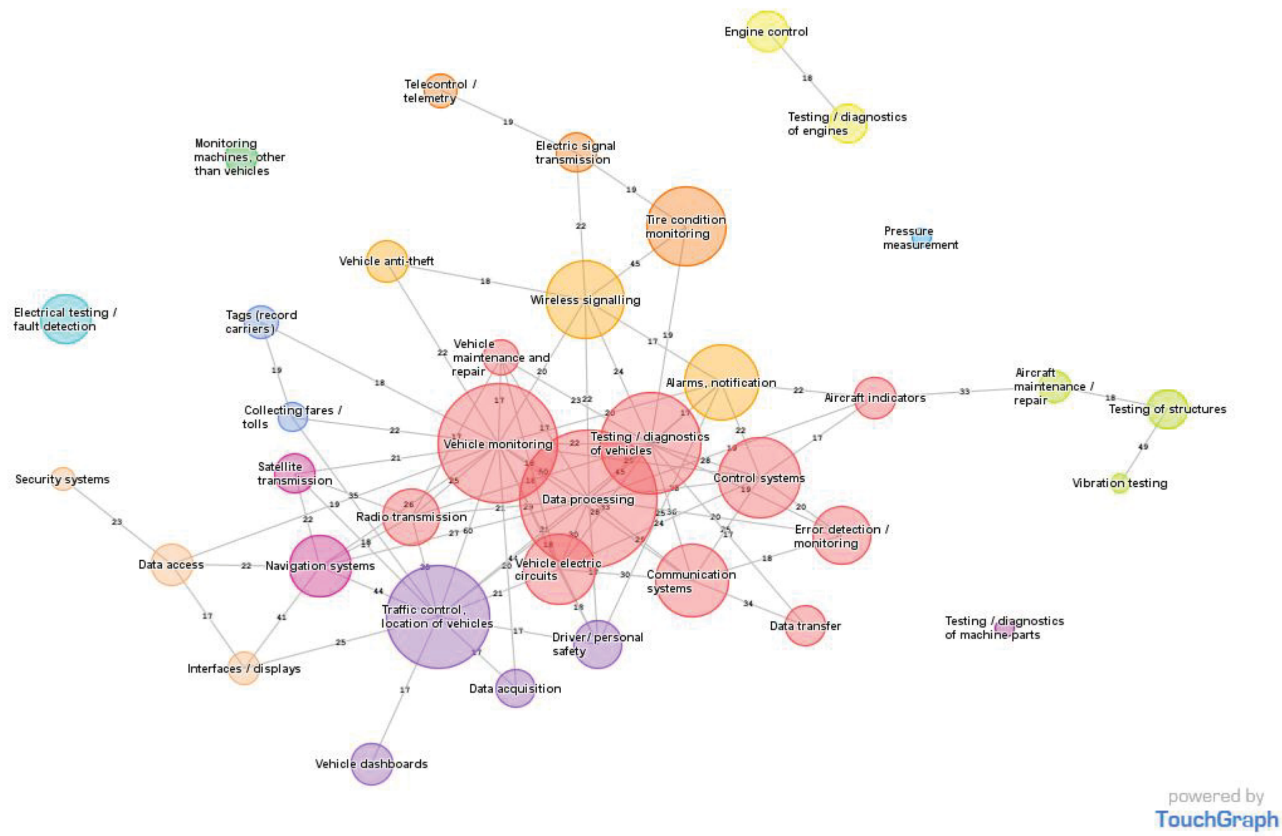

Figure 20. Cluster Map - Patent Subject Groups (correlation > 17%)

When creating the groups shown in Figure 20, attempts were made to make them similar to the literature subject groups, but that was not always possible, primarily because of the differences in the nature of patents versus scientific publications. In Figure 20, a strong emphasis on the data processing and condition monitoring aspects of CBM is shown, but unlike the scientific literature dataset, there is nothing related to sensor technologies and very little specifically related to the health assessment and analytical methods. Since analytics are generally performed by software, their absence from the patent dataset is not surprising given that software is not patentable in all jurisdictions in the world. The absence of sensors is probably due to the fact that sensor technology patents are not necessarily specific to CBM and so are not found in these results.

41% of the patents in the dataset (499/1,204) are related to automotive applications, such as tire condition monitoring and traffic control/location of vehicles. Many of these are related to vehicle telematics – which is mostly accounted for in the *traffic control/location of vehicles* group. Patents in this category describe remote systems for monitoring the condition of a road vehicle and/or its driver and providing live contact with the driver for crisis or crash assistance, such as with General Motors' OnStar[13] system.

When preparing the patent dataset for analysis, patents strictly related to vehicle telematics were excluded, but when there was mention of condition monitoring, they were retained. This likely explains the high incidence of tire condition monitoring patents. To gain better insight into those technologies *not* about telematics and tire condition monitoring, a subset was created excluding these records. When the numbers of patent applications per year for the two datasets are compared, there are some significant differences.

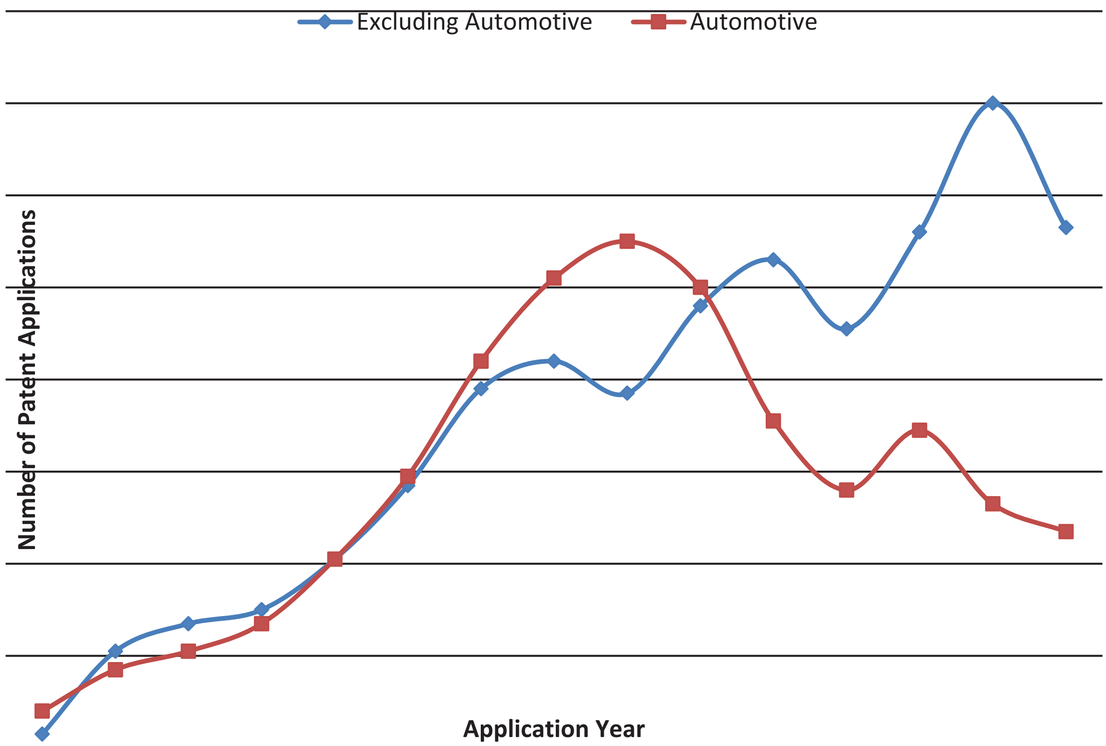

Figure 21. Patent Maturity Curves (1995-2009)

The shape of the s-curves in Figure 21[14] tends to suggest that the automotive applications are more mature than other applications.[15] The automotive dataset curves downwards after 2004, while the

[13] See: http://www.onstar.com/web/portal/home

[14] 2010 and 2011 have been excluded from this graph because of the 18-month delay between patent applications and publication, which means that data for those years are incomplete.

[15] There is much healthy debate in the literature on the value of judging technology maturity based on s-curves, but generally the patent trends tend to consistently follow the same s-shaped pattern. Observations in this report are largely

other curve continues to rise, with only a slight drop in 2009. From this observation one can infer that CBM technology is still in somewhat of a growth period but it may be approaching maturity.

3.3 CBM Systems

An examination of the major topics in the literature shows that CBM systems have applications in aerospace, aircraft, vehicles, electronic systems, civil structures, manufacturing equipment and machinery and others (see Figure 2). A multitude of vendors are operating in these domains, some of them crossing over in different domains and others specializing in specific areas. In addition, the systems available run the entire gamut of the continuum from sensor devices to autonomic logistics software. Frost and Sullivan have observed that few vendors are providing completely integrated predictive maintenance systems (PMS) that cover the entire continuum, but that integrated PMS systems are entering the market for the manufacturing and process industry (Frost & Sullivan 2011).

There are literally hundreds, if not thousands of CBM systems on the market, too numerous to list in one report. For the purposes of this report, only predictive and analytical software are highlighted rather than hardware systems. The following is a list of vendors providing CBM analytical software (also known as health management software), with a focus on military installations. Further details are provided in an attachment to this report (see spreadsheet: 9420 CBM systems.xlsx).

BAE Systems - a primary CBM systems supplier that is also involved with JSF development. Their offerings include the Vehicle Diagnostic Management System (VDMS), and the Vehicle Health Management Ground Support System.[16]
Clockwork Solutions – the SPAR series of products is their main line for CBM and PHM. This company supplies PHM and CBM solutions to many big original equipment manufacturers (OEMs), including Raytheon (ReadiLog Condition Based Maintenance Solution), Boeing, and others.[17]
GE Aviation - IVHM systems have been supplied to Airbus, Boeing and Gulfstream, among others.[18]
Goodrich Corporation - the company has focused on HUMS for helicopters,[19] but they also have a brochure for fixed-wing aircraft diagnostics and prognostics.[20]

based on the hypotheses in this article: Haupt R, Kloyer M, Lange M. Patent indicators for the technology life cycle development. *Research Policy* 36 (2007): 387-398.

[16] http://www.baesystems.com/ProductsServices/index.htm#index-Through-life-Support

[17] http://www.clockwork-solutions.com/app_conditionbasedmaintenance.php

[18] http://www.geaviation.com/systems/products-and-services/avionics.html

[19] http://www.goodrich.com/gr-ext-templating/images/Goodrich%20Content/Enterprise%20Content/Market%20Capabilities/Helicopters/51440_Health_Management.pdf

[20] http://www.goodrich.com/gr-ext-templating/images/Goodrich%20Content/Business%20Content/Sensors%20and%20Integrated%20Systems/Products/Literature%20Listing/Fixed-Wing%20VHMS%20(web).pdf

Impact Technologies – a major supplier of CBM analytical software, with more than a dozen CBM products listed on their website.[21] Their **PHM Design Software** may be of particular interest for planning a PHM implementation.[22]
MACSEA Ltd. – provides DEXTER, a real-time, on-board diagnostic and prognostic technology designed for both maintenance and operating cost reduction, for marine platforms.[23]
Mxi Technologies - an Ottawa company that provides the Maintenix product, now part of the JSF Autonomic Logistics system.[24]
Ridgetop Group – supplier of PHM for electronics systems. Recently signed a contract (Jan. 2012) with Boeing for the development of new CBM technology.[25]
Scientific Monitoring Inc. – provides tools for engine health monitoring, under contract to several large OEMs, including Boeing and Lockheed Martin.[26]

3.4 Interoperability

The term "interoperability", when used in a military context, can mean two things: operational interoperability or technical interoperability (Criscimagna 2002).

Operational interoperability is defined in the U.S. Joint Chiefs of Staff (JCS) Pub 1-02. The definition, which has been adopted by the North Atlantic Treaty Organization (NATO) for use by its member nations, is: "The ability of systems, units or forces to provide services to and accept services from other systems, units, or forces and to use the services exchanged to enable them to operate effectively together" (Criscimagna 2002).

Technical interoperability has a similar meaning and refers to satisfactorily transferring and exchanging information and data across communications and/or data networks and systems. "Thus, interoperability involves interoperation of equipment, interoperation of military forces, interoperation among systems, and the interchangeable use of hardware and software across different kinds of systems" (Criscimagna 2002).

For this report, searches were conducted on the terms "interoperability" and "joint forces", combined with terms for CBM (e.g. CBM, PHM, SHM, etc…). Unfortunately, very few resources were identified which discuss the impact of CBM on joint forces operations. NATO's *Guidance on Integrated Logistics Support for Multinational Armament Programmes* (NATO 2011) directly addresses logistics cooperation among nations. However, the treatment of maintenance practices in this standard is limited, except to say that maintenance planning includes (among other things), "the establishment of maintenance

[21] http://www.impact-tek.com/Resources/ProductTechnologySheetsMore.html
[22] http://www.impact-tek.com/Design%20and%20Systems%20Engineering/PHMDesignSoftware.html. The tool is further described in this 2003 article: : http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA408015
[23] http://macsea.com/systems-solutions/dexter/overview/
[24] http://www.mxi.com/products/maintenix/overview/
[25] http://www.ridgetopgroup.com/products/prognostics/
[26] http://www.sci-mon.com/

programs using condition-based maintenance, reliability-centered maintenance, and/or post production software support" (p.4). Further along in the standard they specify the technical information and data that would be required, where "the objective is to identify the standard(s) to be used for the supply of information and data" (p. 5).
Interoperability is also addressed in US military instructions, however few of them are specifically related to maintenance practices, and in general these instructions provide guidance on what must be taken into consideration for planning and increasing interoperability, but none of them are prescriptive about what should be done. For example, Directive 5000.02 says that program managers (PMs) shall "pursue opportunities throughout the acquisition life cycle that enhance international cooperation and improve interoperability" (p. 74), and in other places there is mention of ensuring interoperability among test and evaluation data (p. 52) and during life-cycle sustainment planning (p.28). DoD Instruction 4630.5 *Interoperability and Supportability of Information Technology (IT) and National Security Systems (NSS)*[27] does not specifically relate to maintenance data but it provides guidance for ensuring interoperability for all information systems across the Department of Defense.

There is some discussion in the literature about interoperability among multi-platform systems (Clark, Vian et al. 2007), but harmonization of CBM practices across nations does not seem to be a current issue of discussion for the CBM community. Nevertheless, one can find evidence of a call for and use of open standards for two key technology areas: sensor interoperability and data interoperability.

As already noted, sensors and wireless sensor networks are key enablers of CBM systems. Lee writes:

> Due to the diversity of sensor system and network requirements for existing sensors and detectors, and future systems and sensors and systems, information networks must be able to support heterogeneous, multi-vendor networks. Thus, a framework for interoperability is necessary to accommodate these systems and networks. Furthermore, a framework of open, consensus-based standards is needed to connect many sensor networks into one large network (Lee 2007, 384).

Several standards initiatives are underway to address sensor interoperability for military purposes, including CBM. The Machinery Information Management Open Systems Alliance (MIMOSA)[28] was organized to establish an open architecture and a set of protocols for exchanging information between CBM systems. Similarly, the Open System Architecture for Condition Based Maintenance (OSA-CBM) program has developed an open architecture and standard for distributed CBM software components. The OSA-CBM standard[29] is an implementation of the ISO-13374 functional specification *Condition Monitoring and Diagnostics of Machines,* which defines six blocks of functionality in a condition

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[27] See http://www.dtic.mil/whs/directives/corres/pdf/463005p.pdf
[28] See http://www.mimosa.org/
[29] Available from MIMOSA at: http://www.mimosa.org/?q=resources/specs/osa-cbm-321

monitoring system, as well as the inputs and outputs of those blocks. OSA-CBM provides an open architecture for the six blocks, as well as defining the interfaces between the blocks. However, according to Lee, neither MIMOSA nor the OSA-CBM specification defines a sensor interface or communication protocols for acquiring sensor data. The IEEE 1451 suite of standard provide ways to interface sensors and actuators to instruments and networks, including the Web, "which can play a key role in completing the process from the acquisition of data at the sensor level to the transfer of the sensor information to the enterprise level, where MIMOSA and OSA-CBM are set up to manage the information (Lee 2007, 385).[30] In addition to the 1451 standards, the Sensor Web Enablement (SWE) specifications[31] developed by the Open Geospatial Consortium (OGC) provide an "open platform for exploiting Web-connected sensors and devices" (Lee 2007, 382).

Data interoperability is of particular importance when implementing CBM with legacy systems, as discussed by Clark, Vian et al. in their paper on the Integrated Airplane Health Management (IAHM) program led by the Boeing Company for the U.S. Navy (Clark, Vian et al. 2007). In their paper, the authors describe how the MIMOSA open standard was used as a basis for the database schema design of the IAHM system. The generic database schema was designed to be applicable to aircraft, test stations, ships and land vehicles, however, it should be noted that the standard was not applicable for all data the project team wished to monitor and so customization was necessary. In a companion paper from the same year, Shawver, Hanson et al conclude (Shawver, Hanson et al. 2007):

> In the field of aircraft health management, the lack of data accessibility and integration is a major hurdle and maintaining historical data will be important in the development of future health management systems. The size of centralized data repositories, the availability of protocols for integrating disparate system, and the constraints on communication bandwidth are hurdles that must be addressed to achieve data accessibility and integration (p. 12).

Careful planning for data accessibility and integration is therefore seen as a crucial step for successful CBM implementation.

A list of CBM-related standards is provided in Appendix 10.3.4. In addition, the articles by (Sheppard, Kaufman et al. 2008) and (Tobon-Mejia, Medjaher et al. 2010) discuss CBM-related standards from IEEE and ISO respectively, and are good sources to help understand the practical application of the standards. The IEEE standards known as AI-ESTATE and SIMICA are two important standards for PHM implementation in particular. The AI-ESTATE standards provide mechanisms for exchanging diagnostic information, while the SIMICA suite of standards is focused on historical usage information and provides a means for using that information to improve both diagnostics and prognostics (Sheppard, Kaufman et al. 2008).

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[30] A list of applicable MIMOSA and IEEE standards is found in Appendix 10.3.4 of this report.
[31] See http://www.opengeospatial.org/projects/groups/sensorwebdwg

4 BENEFITS, RETURN ON INVESTMENT

The goal of this section is to summarize the accepted benefits of CBM in general and to provide an overview of the metrics and measures of cost-benefits. A list of articles that explain *how* to do a Return on Investment (ROI) analysis or cost-benefit analysis (CBA) is provided in Appendix 10.3.1. Finally, details on a few case studies of ROI analysis for implemented systems are provided.

4.1 Benefits of CBM

An understanding of the desired process improvements and business needs should form part of any CBM implementation plan. Key motivators for implementing CBM systems are productivity improvements and improved business processes, which benefit both the organization and the maintainers. These improvements lead to business advantages but are not always measurable in monetary terms. These advantages may be seen in terms of greater productivity, shorter maintenance cycles and better use of resources (CBM+ Guidebook, p. 3.5), and are usually expressed as percentage increase or decrease. The non-monetary benefits include the following:

- Productivity improvements
- Improved business processes
- Reduced accidents, improved safety
- Improved perception of safety, morale and operator performance
- Improved system availability
- Improved equipment reliability
- Extended equipment life
- Enabling of logistics systems response, assists logistical support system design
- Reduction in footprint (for military systems).

Improved safety and reduction of accidents are key benefits cited in several reports reviewed for this study. Obviously, if systems are well maintained and there are advanced warnings of potential failures, the likelihood of accidents is reduced and in the case of aircraft or other vehicles, potentially disastrous or fatal accidents may be avoided (Sun, Zeng et al. 2010).

One study reviewed for this paper gathered data from a focus group of pilots and crew chiefs and found that after implementing a CBM system, there was an improved sense of safety among operators as well as improved performance, morale and confidence (Bayoumi, Goodman et al. 2008).[32]

[32] See section 4.4.1 for further details on this study.

Improved system availability is another benefit of CBM that cannot always be measured in monetary values but is a key benefit in all application areas. In a military context, system availability refers to the operational readiness of platforms and in an industrial context these benefits translate to uninterrupted productivity because plant equipment is more available. These benefits can be measured in terms of reduced system downtime, as discussed in the metrics section below. Similar to system availability, system reliability can be improved by CBM since a component can be replaced before the end of its useful life, leading to less unexpected downtime. In addition, maintenance planning is improved because parts are being replaced as needed and so downtimes can be avoided or planned for more effectively.

Another expected benefit of CBM implementation is that it can enable enhanced maintenance-centric logistics system response, also referred to as autonomic logistics, discussed in Section 6. Sun, Zeng et al. briefly describe CBM as enabling logistics support system design by reducing the need for logistical system infrastructure because there would be less need for spare parts depots, less inspection and maintenance equipment required and less need to have large maintenance crews on hand (Sun, Zeng et al. 2010). These benefits are related a reduced footprint, which is "a measure of weight and space required, in terms of cargo airplane loads to move an entire squadron of aircraft from one base of operations to another" (Byer, Hess et al. 2001). In other words, fewer people and less support equipment results in fewer cargo aircraft loads needed to move a military squadron to a new base of operations, and therefore a smaller footprint.

In addition to the above benefits, the DoD *CBM+ Guidebook* cites benefits at the tactical, operational and strategic levels in that better data is available to planners on weapons and platform availability and readiness and can therefore enhance command situational awareness at the weapon system level (p. 1.7).

While we have discussed the potential benefits of CBM in terms of system safety, reliability, maintainability and logistics, the benefits of primary concern to decision makers are reductions in operational and support costs. According to the DoD, operational and support costs (O&S) represent 65-80% of life cycle costs (CBM+ Guidebook, p. 1.1). For predictive maintenance systems, cost benefits are usually found in cost avoidance.

The areas where cost savings can be realized and measured include (Sun, Zeng et al. 2010):

- Reduced regular inspection costs
- Avoiding costs due to system downtime
- Reduced costs in spare components and simplification of the supply chain for spares – as well as using parts for longer
- Avoiding costs in direct and indirect manpower

    - Less time on direct maintenance and inspection hours
    - Less need for a maintenance crew to set up and use ground test equipment
    - With less direct manpower, less indirect manpower is required (i.e. support staff)
    - Less maintenance staff means less spent on training
- Avoiding collateral damage during repair
- Reduction in number of no faults found
- Reduced liability for failures

The measurement and calculation of cost-benefits are essential for producing a business case in support of CBM implementation and are discussed in more detail in section 4.2 below.

4.2 Measures and Metrics for Cost-Benefit Analysis

The following section lists some of the common measures used in cost-benefit analysis and briefly summarizes the guidelines for creating a business case. Further details on the latter aspect can be found in the DoD *CBM+ Guidebook* and several other publications that are highly recommended: (Byer, Hess et al. 2001; Fischer 2011; OSD CBM+ Action Group 2010; Feldman and Sandborn 2008). Additional references on Cost-Benefits Analysis (CBA) guidelines are found in appendix 10.3.1.

The following section is copied directly from the DoD *CBM+ Guidebook* (pp. 1.5-1.6) and is useful to understand when reading other studies on cost-benefit analysis, particularly for military organizations:

- Materiel availability (MA) is a measure of the percentage of the total inventory of a system that is operationally capable (ready for tasking) of performing an assigned mission at a given time, based on materiel condition. It can be expressed mathematically as the number of operational end items divided by the total population. Materiel availability also indicates the percentage of time a system is operationally capable of performing an assigned mission, and can be expressed as uptime divided by the sum of uptime and downtime.
- Materiel reliability (MR) is a measure of the probability the system will perform without failure over a specific interval. Reliability must be sufficient to support the warfighting capability needed. Materiel reliability is generally expressed in terms of a mean time between failures (MTBF), and, once operational, can be measured by dividing actual operating hours by the number of failures experienced during a specific interval.
- Ownership cost (OC) balances the sustainment solution by ensuring the O&S costs associated with materiel readiness are considered when making decisions. For consistency, and to capitalize on existing efforts in this area, the Cost Analysis Improvement Group's O&S Cost Estimating Structure supports this key system attribute.
- Mean down time (MDT) is the average total time required to restore an asset to its full operational capabilities. MDT includes the time from reporting of an asset being down to

the asset being given back to operations or production to operate. This measure has been identified as an important metric to measure operational availability.

Other measures found in the literature include:

- Mean Flight Hours Between Maintenance Events (MFHBME),
- Mean Flight Hours Between Maintenance Removals (MFHBMR)
- Mean Time To Repair (MTTR) (sometimes called Mean Time to Restore)
- Mean Logistics Down Time (MLDT)
- Flight Hours (FH) – where an increase in flight hours is expected for aircraft with a CBM system on board
- Operational Readiness (OR) rates (similar to Materiel Readiness, cited above) – this is usually broken down into its two reportable components: Fully Mission Capable (FMC) and Partially Mission Capable (PMC)
- Non-Mission Capable for Maintenance (NMCM) – the time, in hours, that an aircraft is not airworthy due to required maintenance actions (scheduled) or faults discovered during flight or inspection (unscheduled)
- Maintenance Test Flights (MTF)
- Maintenance Man Hours (MMH).

In the preparation of a business case or a CBA, the task becomes one of determining the cost differences between the platform with and without PHM (Byer, Hess et al. 2001) (or SHM, or IVHM, whatever the case may be). Historical cost data therefore must be used for comparison and often already exists in procurement or maintenance databases.

4.3 Cost-Benefits Analysis Tools

There are several software products on the market that may help to model and test cost-benefits for health management systems.

US Army Research Laboratory (ARL) Trade Space Visualizer (ATSV)
This tool is based on methods proposed by Herbert Hecht (Hecht 2006) for calculating cost avoidance in terms of mean time to restore (MTTR) and operational availability. These measures are subject to a number of variables that can be tested using the ATSV tool. Banks and Merenich provide a good general overview of the ARL Trade Space visualizer (ATSV) software and how their method has been used to test cost benefits and ROI on battery prognostics by testing a multitude of variables (Banks and Merenich 2007). More details on the tool can be found at: http://www.atsv.psu.edu/whatisatsv.html .

CALCE Maintenance Planning Tool
This tool appears only to be available to members of the Centre for Advanced Life Cycle Engineering (CALCE) at the University of Maryland but it may be available for purchase upon inquiry. According to

their website, the tool was recently enhanced to model implementation costs and infrastructure costs. http://www.prognostics.umd.edu/CALCE_Planning_Tool.html

Boeing - Ownership Cost Calculator for Aerospace Health Management (OCCAM)
Wilmering and Ramesh of Boeing describe an analytical tool called the Ownership Cost Calculator for Aerospace Health Management (OCCAM), but this tool does not appear to be commercially available unless its name has changed since 2005 (Wilmering and Ramesh 2005).

Total Life Cycle Management Assessment Tool (TLCM-AT)
This tool, developed by Clockwork Solutions, was described by Fischer in 2011 (Fischer 2011), but it appears that the tool has been renamed and is now called Total Life Cycle System Management: http://www.clockwork-solutions.com/app_totallifecyclesystemmanagement.php .

4.4 CBM Implementations

The following section highlights six studies and research programs in which CBM systems were evaluated and for which figures on cost benefits were reported. There are many more studies available however few of them provide actual cost and benefits figures. Benefits and savings are summarized below, but for more technical details, one should consult the references provided.

4.4.1 University of South Carolina and the South Carolina Army National Guard

A series of articles by Bayoumi, Goodman et al. were published in 2008, which discuss a CBM research program for helicopter maintenance. The program's goal was to collect and analyze data in order to formulate requirements for and assist in the transition toward CBM for the Armed Forces. Their study was conducted on Apache and Blackhawk helicopters, starting with 18 aircraft in 2000, but eventually included more than 100. The study used HUMS data from the Army-developed Modern Signal Processing Unit (MPSU) and the Vibration Management Unit (VMU). The MPSU aquires data and calculates the Condition Indicators (CIs) used to determine the health of the drive system mechanical components (Blechertas, Bayoumi et al. 2009). The VMU focuses on vibration levels of specific components during flight.

A summary of technical details for CBM research at USC was presented at the American Helicopter Society Technical Specialists' Meeting on CBM in 2009 (Blechertas, Bayoumi et al. 2009) and more information on their research program can be found on their website.[33]

[33] http://cbm.me.sc.edu/index.htm

One article in particular discusses the cost-benefit analysis that was performed (Bayoumi, Goodman et al. 2008). The article provides a good description of the methods for establishing a baseline from historical maintenance records and test data and how these data are used for cost-benefits analysis (CBA).

For the period 2000-2007, the project observed the following benefits:

- Savings in parts costs: $1.4 million
- Savings in parts and operational support: $2.1 million
- Cost reduction of $2.2 million in maintenance test flights, with an expected annual savings of $18K per aircraft
- "Soft" benefits:
    - Increased mission capable rates through a decrease in maintenance test flights and an increase in total flight time
    - Improved safety, sense of safety, morale and performance.

4.4.2 U.S. Army Materiel Command – Heavy Expanded Mobility Tactical Trucks (HEMTT)

A 2011 report by Fischer describes an ROI analysis for a CBM+ pilot project on a tactical vehicle platform, the HEMTT (Fischer 2011). In general, the results of the analysis showed an approximate $10M cost savings across a Stryker Brigade Combat Team (SBCT) of 1045 vehicles in the first 10 years of operation. In the final tally, a net cost savings was observed, with an ROI realized after 10 years. However, when calculated over the entire fleet, the ROI was only $717 per year per platform and so it was not deemed cost-effective to implement CBM+ capabilities on the proposed platforms.

This study is interesting because it reports on the enabling costs (i.e. the costs associated with implementing a CBM system), as well as the cost savings. The study suggests that the implementation costs of a CBM system ranges from $1,000 to $7,500 per vehicle (see table 2 in the paper). However, when all implementation costs are factored in, they report a cost/platform of $15,000 (Fisher 2011, 29).

In addition, this study took into account the effects and costs associated with autonomic logistics systems, which many other studies do not. Factors for shipping times and logistic consequences are included in the model, for example (see pp. 13-14). The tool used for analysing cost-benefits for this project was the Total Life Cycle Management Assessment (TLCM-AT) from Clockwork Solutions Inc.

The authors do note several important caveats to their analysis, primarily the lack of real data and the fact that many assumptions had to be made. Historical usage and cost data is of primary importance when conducting cost-benefits analyses and so a choice of case studies for testing CBM implementation should be made based on whether this type of data is available. Similarly, one of the challenges of proving ROI is that cost savings may not be realized until several years have passed and so investment may be difficult to justify at first.

4.4.3 U.S. Army Aviation Command (AMCOM) – UH-60 Blackhawk Helicopters

A 2009 master's thesis by Gaguzis provides a complete benefits analysis of HUMS installations on UH-60 Blackhawk assault battalions over a five year span (Gaguzis 2009). The goal of the study was to compare the effectiveness of CBM over periodic or phase maintenance. In addition to providing hard data on the benefits and limitations of CBM, this thesis provides extensive discussion on metrics (both those that were used and those that were rejected), as well as an objective literature review.

The study compared two UH-60 Blackhawk battalions – one unit with Goodrich Corporation HUMS systems installed and one without HUMS. The Goodrich system uses a series of sensors or accelerometers to detect and measure vibrations in the aircraft. "Each sensor is placed at a critical location on the airframe in order to monitor a specific component. These accelerometers can detect vibration discrepancies from an imbalance, misalignment, mechanical looseness, gear mesh, rotor systems, mechanical impedence or natural frequency" (Gaguzis 2009, 6).

The results that were observed over the 5-year time period were:

- 10.2% flight hour (FH) improvement
- 4.4 - 5.2% increase in operational readiness for all three airframe types
- 13.9% increase in mission capable hours
- 6.9% decrease in Non-Mission Capable for Maintenance (NMCM) time.

The report is less definitive about the cost savings observed and states many caveats with their cost analysis, however the figure that is reported is a 30.9% cost advantage for the HUMS units.

4.4.4 U.S. Army Aviation and Missile Life Cycle Management Command (AMCOM)

Two presentations were identified related to AMCOM's CBM program (Nenninger 2007; Smith 2011).

The objectives of the AMCOM CBM program are to:

- Decrease maintenance burden on the soldier
- Increase platform availability and readiness
- Enhance safety
- Reduce O&S costs

Similarly to the AMCOM study reported in section 4.4.3, this program measured vibration levels on Army helicopters for more than 50 different parts and rotating components on each aircraft. Further details on the parts tracked are provided in the Nenninger presentation of 2007 (Nenninger 2007).

4.4.4.1 2007 report

The following data was extracted from a presentation by Gary Nenninger at the DoD Maintenance Symposium in 2007 (Nenninger 2007). The results were presented by type of platform and cover an 9 month period (Oct. 2006-July 2007):

Table 1. AMCOM CBM Program - Cost Benefit Results

	AH-64 (171 aircraft)	UH-60 (143 aircraft)	CH-47 (30 aircraft)
Efficiencies Overall	$2.1M	$295K	$128K
Readiness	1% increase	3.3% increase	1% increase
Maintenance Man Hours (MMH) Avoided	2,254 hrs	1,237 hrs	632 hrs
Downtime Avoided	355 hrs	673 hrs	203 hrs
Maintenance Test Flights (MTF)	513 hr reduction	147 hr reduction	32 hr reduction

Finally, in terms of units operating, the author reports the following benefits for 2005-06:

- 5% increase in FMC gives 1.5 more aircraft
- 1,432 increase in hours flown = 2 more aircraft at OPTEMPO (i.e. hours/year/aircraft)

4.4.4.2 2011 report

The director of the AMCOM CBM Program, Christopher Smith, provides many details on cost savings and operational metrics for several type of aircraft (Smith 2011).

Smith reports on CBM metrics for the 2011 Fiscal Year, for 2,443 aircraft equipped with CBM, as follows:

- 4-12% NMC (non-mission capable) reduction
- 5-8% increase in Readiness
- 1-4% reduction in Maintenance Test Flight
- 1 less Mission Abort per 100 Flt Hrs
- Avoided 4 Class A (Major) mishaps
- 6-9% decrease in aircraft maintenance non-available
- Over 127 maintenance procedures improved or eliminated

For cost avoidance benefits, the author cites the following figures:

- Four (4) aircraft Class A accidents avoided: ~$49M
- 57 UH60/AH64 engines not replaced: ~$27M
- 12-22% Class IX cost reduction

Further details by aircraft type are found in the 2011 presentation.

4.4.5 U.S. Navy - Integrated Condition Assessment System (ICAS)

The U.S. Navy has described their ICAS system in several papers and presentations since 2002 (DiUlio 2002; DiUlio, Savage et al. 2003; Department of Defense 2011). ICAS is a Commercial off the Shelf (COTS) software product that was developed in a shell-type architecture to allow for varied implementation of machinery monitoring and CBM. The tool was developed by IDAX Inc., a subsidiary of GE Power Systems. The systems it monitors include propulsion systems, bearings, fuel oil, lubrication, air conditioning and refrigeration systems, and many others (DiUlio, Savage et al. 2003).

In 2003, it was reported that ICAS had been installed on more than 95 Navy ships (DiUlio, Savage et al. 2003). The ROI and cost-benefits information on this system are not always the same in all reports found in our search, however. Furthermore, attempts to contact the original authors have not resulted in any reply for clarification, so the following results must be considered tentative until they can be confirmed. The data from the first source (Department of Defense 2011) states that the figures are taken from two separate studies, the first from 1999-2001 compared 13 ICAS ships to 14 non-ICAS ships and the second, from 2002-2003, compared 14 ICAS ships to 13 non-ICAS ships, meaning that at most, 54 ships were involved in the study. In the second source (DiUlio 2002), 13 CG-47 Class ships with ICAS installed are compared to 14 ships without ICAS.

The following cost-benefits (Table 2) have been reported in two different sources and cover the period 1999-2003.

Table 2. Savings and Return on Investment for Navy ICAS Study

Description	Reported in (Department of Defense 2011)	Reported in (DiUlio 2002)
Annual Savings (Existing Installs)	$6.6M 165.2 man-years	$6.1M / yr (this was also reported as $12.7M *potential* savings, if the 14 ships without ICAS were counted)
Class Wide for 15 Life Yr Span	$192M 4,779 man-years	Not reported
Savings & Manpower Reduction		
• **Maintenance Savings:**	$347K / ship / year	$152K / ship / year[34]
• **Fuel Usage:**	$126K / ship / year	$ 90K / ship / year
• **Logsheet Manhours**	Not reported	$ 230K/ship / year
• **Total Savings:**	$473K / ship / year	$472 / ship / year
Payback	11 months	1 year (projected)
Return on Investment	3.55 (ratio)	Not reported

4.4.6 Boeing 737 – ROI for PHM of Electronic Products

Feldman and Sanborn report on a case study of a multifunctional display in a fleet of 502 Boeing 737, which compared the life cycle costs of a system employing unscheduled maintenance approaches to the same system using a precursor to failure PHM approach (Feldman and Sandborn 2008). Their report provides extensive discussion of the methods for calculating ROI, expressed as a ratio in which ROI greater than zero implies that there is a cost benefit. In addition, the paper cites numerous ROI studies that have been performed for PHM systems on aircraft since 2000.

The results for the Boeing 737 study include:

- 91% of failures were avoided
- ROI was calculated to be approximately 3.131

The authors conclude that “allowance for variability in cadence, false alarm, random failure rates, and system size enables a more comprehensive calculation of ROI to support acquisition decision making” (Feldman and Sandborn 2008, 8).

[34] This figure is cited as O-Level Maintenance, which is probably operational level, and it relies on data of only 10 ships from 1999-2002, where the other source was based on 13 ships and covers and additional year, and likely includes the logsheet manhours savings, though it is not specified.

5 BARRIERS AND DRIVERS TO ADOPTION

5.1 Drivers

Many of the drivers for adoption of CBM are the same as the cited benefits: to enhance safety; to improve business and maintenance processes; and to reduce O&S costs. These drivers are cited in many of the documents reviewed for this report. In addition, there are some drivers that are particular to different applications and markets.

For the U.S. military, the adoption of CBM is largely due to several directives on maintenance and acquisitions that have been issued in recent years. In May 2003, the DoD issued the 5000.2 policy (Department of Defense 2003), which states that:

> PMs [program managers] shall optimize operational readiness through affordable, integrated, embedded diagnostics and prognostics, and embedded training and testing; serialized item management; automatic identification technology (AIT); and iterative technology refreshment (section 3.9.2.4, p. 15).

This policy applied to all defence technology projects and acquisition programs, including acquisitions of services. It was modified in 2008, where the section regarding prognostics reads: "PMs shall optimize operational readiness via… diagnostics, prognostics and health management techniques in embedded and off-equipment applications when feasible and cost-effective"(Department of Defense 2008, 29).

In December 2007, the CBM+ policy, DoD Instruction 4151.22 (Department of Defense 2007) was issued, which "provides an integrated strategy for deployment of enabling technologies, processes and procedures that focus on a broad range of weapon system sustainment improvements" (Deputy Under Secretary of Defense for Logistics and Materiel Readiness 2008, iii). Under the umbrella of the Total Life Cycle System Management (TLCSM) program, CBM+ supports the larger DoD improvement effort "with the goal of delivering cost-effective joint logistics performance by maximizing weapon system and availability through a more effective logistics process" (CBM+ Guidebook, p. 1.2). A key objective of the CBM+ policy, therefore, is to increase materiel readiness.

Also in December 2007, the Army Acquisition Executive approved a new *Army Reliability Policy*. The policy "encourages use of cost-effective reliability best practices and provides a mechanism to alert key Army leaders when weapon systems are off track with respect to meeting their reliability requirements" (Drake 2010). These reliability requirements are also reflected in the most recent Army Acquisition Policy (Army Regulation 70-1) from July 2011, which contains several clauses related to platform and weapon reliability, Performance Based Logistics (PBL), and the use of Item Unique

Identifiers (IUID). It also includes the following directive for Program Managers (Department of the Army 2011, 9):

> Incorporate condition based maintenance plus (CBM+) concepts and technologies in the design and development of new equipment and major weapon systems, and in current weapon systems, equipment, and materiel sustainment programs where it is technically feasible and beneficial. The decision for implementing CBM+ to current weapon systems, equipment, and materiel sustainment programs will be based on any of the following:
>
> (1) Results of reliability analyses, including reliability centered maintenance.
> (2) Findings from continuous process improvement initiatives.
> (3) Technology assessments.
> (4) Business case analysis.

There is clearly significant direction from the US military to pursue CBM+ across the DoD, which in part is driving the market for predictive maintenance technologies, particularly in the US.

For non-military markets, such as manufacturing and transportation, the drivers are similar – to increase productivity as a result of better equipment reliability and availability and to reduce O&S costs. In the case of aircraft, proponents of DPHM say that CBM systems are key factors for achieving improved airworthiness levels and reducing catastrophic failures (Industry Canada 2004).

On the technology side, Frost & Sullivan cite the following capabilities that are driving improvements to and adoption of predictive maintenance systems for manufacturing industries (Frost & Sullivan 2007):

- Affordable hardware for communications systems, such as Zigbee, Wi-Fi and Bluetooth devices
- Data communication enabled by cellular networks, where machine data can be transferred at a nominal cost
- Better processing power for embedded, local systems and for central analysis units
- Improved and more reliable sensors, particularly MEMS sensors. Increased use in high volumes increases economies of scale and drives down the cost.

5.2 Barriers and Challenges

The main barriers and challenges to CBM adoption can be summarized as follows:

- High acquisition and installation costs make short term ROI difficult to realize
- Difficulty in calculating ROI and conducting cost-benefit analyses
- Prognostic accuracy and selecting appropriate prognostic methods
- Need for appropriate metrics and measures to assess prognostic accuracy

The barriers and challenges for the predictive maintenance market are remarkably parallel to the main drivers, as noted in a 2004 Industry Canada report on DPHM technologies for aircraft. They write (Industry Canada 2004, 10):

> In essence, the market constraints not surprisingly mirror the market drivers as:
> - Cost of acquisition, implementation an ownership – of the DPHM systems
> - Reliability and availability of the DPHM systems and their output; and
> - Airworthiness/flight safety standards cannot be adversely affected by the fitment of DPHM system, this self-evident concept has been overlooked in the past when unproved technology implementations occurred too early

So while CBM systems are expected to save money in the long run, they do require significant expenditure for acquisition, implementation and ownership. Another constraint is the reliability and availability of the prognostic systems themselves – improvements to sensors and analytical algorithms are still needed to reduce false alarms.

Another point made by Industry Canada is that with better fault diagnostics, sometimes unexpected faults are identified in which maintenance personnel have little experience troubleshooting or knowledge of, and this can sometimes mean that a relatively minor fault can result in extended out-of-service periods (Industry Canada 2004, 10).

For the manufacturing and process industry, Frost & Sullivan state the following main challenges (Frost & Sullivan 2011):

- Slow rate of advancements in core sensor technology and drawbacks of MEMS sensors for predictive maintenance (PdM)
- Slow rate of adoption of PdM software
- Lack of diversification in monitoring of PdM
- Low short-term ROI
- Installation barriers of web-based PdM systems may lead to slower adoption rate for advanced PdM systems. Most plants lack the communication infrastructure necessary to install, run, and maintain web based systems.

Installation costs and technical challenges should not be discounted in any proposed CBM implementation. In writing about PHM systems for electronics systems, Sun et al list the following barriers (Sun, Zeng et al. 2010):

- Selection of applicable prognostics methods, implementers need to choose between
    - Data driven vs. Physics-of-failure (PoF) methods,
    - or hybrid methods.

- Addressing inherent uncertainties and assessing prognostic accuracy
  - Need to account for uncertainties
  - Need metrics and methods to impartially measure and evaluate the performance of a PHM system.
- Difficulties in proving ROI
  - Difficult to quantify the benefits of PHM results
  - Have to take into consideration the impact on overall logistics support systems and other related resources
  - Calculating ROI is a challenging multi-objective and multi-attribute trade off and a complex decision making problem.

6 AUTONOMIC LOGISTICS

A definition of autonomic logistics (AL) is provided by Byer, Hess et al as "simply the application of automation to locating and ordering repair parts so that they are available when needed" (Byer, Hess et al. 2001). This definition is rather simplistic in that it does not convey the complexity of the problem, or its relation to prognostics and health management. The authors continue by pointing out that inventory management systems have been in place for decades, but that it is the link to maintenance and health management that differentiate autonomic logistics from traditional inventory or asset management systems. Instead, one might define AL as "a knowledge-based logistic system that identifies and communicates maintenance requirements, supply chain management issues, parts reliability, and safety and training information in order to support and enhance mission execution" (Byer, Hess et al. 2001). This definition is closer to what is also known as Sense & Respond Logistics (S&RL).

S&RL, both as a concept and as a program, is specifically defined for the US military as follows (Department of Defense 2006):

> Sense and Respond Logistics relies upon highly adaptive, self-synchronizing, and dynamic physical and functional processes, employing and enhancing operational cognitive decision support. It predicts, anticipates, and coordinates actions that provide competitive advantage spanning the full range of military operations across strategic, operational and tactical levels of war (p.1).

While S&RL does not specifically relate to maintenance in the same way that AL does, predictive maintenance functions are a significant, enabling part of S&RL.

The DoD *CBM+ Guidebook* (Deputy Under Secretary of Defense for Logistics and Materiel Readiness 2008) lists several logistics programs that CBM+ is related to, including Total Life Cycle System Management (TLCSM), Reliability Centered Maintenance (RCM), Performance Based Logistics (PBL) and Sense & Respond Logistics (S&RL). All of these DoD programs and initiatives address different points along the supply chain and generally, CBM+ is seen as an enabler of more effective life cycle management, maintenance scheduling and management, and logistics cost control (see section 5.4 of the *CBM+ Guidebook*). The following quotes are excerpts from the *CBM+ Guidebook* which highlight the relationship between CBM+ and the corresponding programs.

> TLCSM implementation is an incremental and continuous effort to ensure all valid support requirements are identified and included in requirements and funding programs at each acquisition milestone… CBM+ contributes to a number of process improvement initiatives to attain the life-cycle support objectives of system effectiveness and affordability (p. 5.5).

> The synergy between RCM and CBM+ relates to the use of applicable CBM+ technologies and methods to support management decisions for selecting and executing maintenance tasks. By linking RCM and CBM+ as complementary management tools, maintainers can significantly strengthen the rationale for choosing the most technically appropriate and effective maintenance task for a component or end item (p. 5.5).
>
> PBL is an approach for weapon system and equipment support that employs the acquisition of support from "best value" sources as an integrated, affordable performance package designed to optimize system readiness. As CBM+ helps focus the maintenance process on maximizing weapons and equipment readiness with optimum resource allocation, it fully complements the PBL concept. In fact, it becomes an essential factor in attaining the performance-based objectives in the area of maintenance (p. 5.5-5.6).
>
> S&RL depends on sophisticated IT support to enable data sharing, early intelligence, commitment tracking, predictions, adaptation, and cognitive decision support. Under the S&RL concept, most military end-items and systems will be equipped to sense potential component failures or consumables support status… In the long term, S&RL will expand predictive capabilities across the spectrum of logistics functions. CBM+ is an initial application of the S&RL concept (p. 5-7).

In summary, AL uses CBM+ outputs to enable: system effectiveness and affordability; management effectiveness for selecting and executing maintenance tasks; performance-based logistics related to system readiness; and effective decision support across all logistics functions.

The functions of an Autonomic Logistics system for military applications include (Henley, Hess et al. 2001):

- mission planning,
- maintenance action scheduling,
- ordering and tracking of spare parts (i.e. asset tracking),
- scheduling of flight and maintenance training,
- assignment of specific pilots to specific missions based upon experience and readiness,
- assigning specific aircraft to specific missions based upon aircraft availability and capability,
- storing maintenance, training, spare part, and logistic information in a data warehouse.

6.1 Technology Trends

Based on an analysis of the dataset gathered for this project, topics related to AL do not feature prominently in the literature of the CBM community. Figure 22 illustrates the numbers of publications for subject groups related to logistics and supply chain management in the complete dataset of 4,394 records. For all the topics, interest is clearly declining. This trend is likely due to the fact that research is currently still focused more on sensors and prognostic and diagnostic accuracy, as we have seen in previous sections. As well, because the search did not specifically include logistics or supply chain as terms, the dataset focuses on the maintenance aspect and may not accurately reflect all the activity taking place on the logistics side. For a more detailed review of S&RL in general and asset tracking technologies in particular, the 2010 NRC-CISTI report *Sense & Respond Logistics* (Keating and Brady 2010) may be helpful. Asset tracking technologies, such as Radio Frequency Identifiers (RFID) will not be treated in depth in this report but some general trends are observed in the sections that follow.

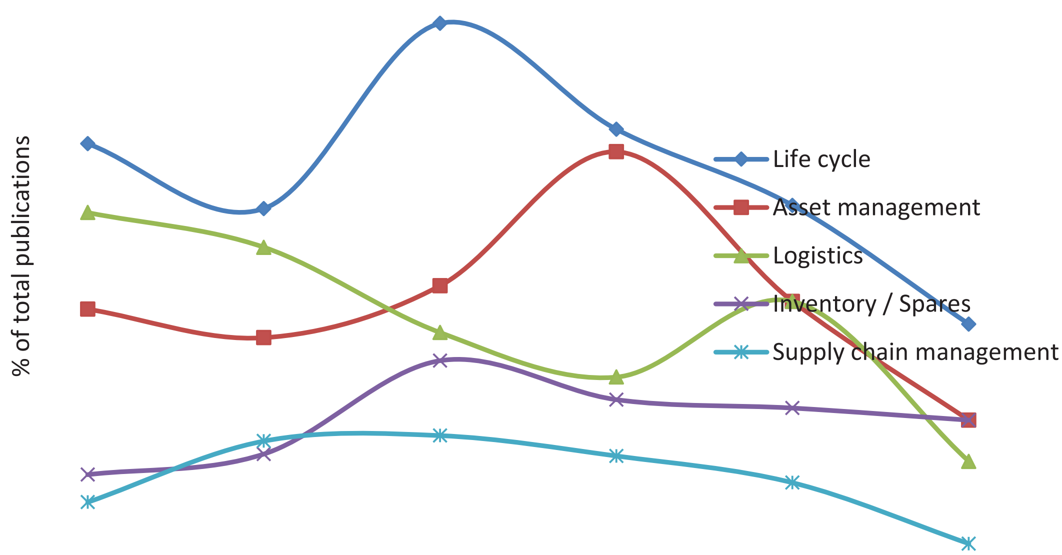

Figure 22. Logistics Topics - % of Total Publications per Year

For a more detailed view of research trends for logistics as they relate to CBM, a sub-dataset was created, containing 455 records and representing 10.3% (455/4,394) of the original dataset. Figure 23 below shows the subject groups created for the logistics subset and their relations to each other. In this figure, the importance of *Decision Support* and *Information systems* are made evident (yellow-green, in centre), as well as *Asset tracking, RFID* and *Sensors* and *Sensor networks* (in blue at left). The red cluster in centre, right shows some of the largest subject groups, all closely related to each other and similar to the major groups shown in other parts of this report (i.e. *Condition Monitoring, CBM, Diagnostics, Prognostics,* etc*)*.

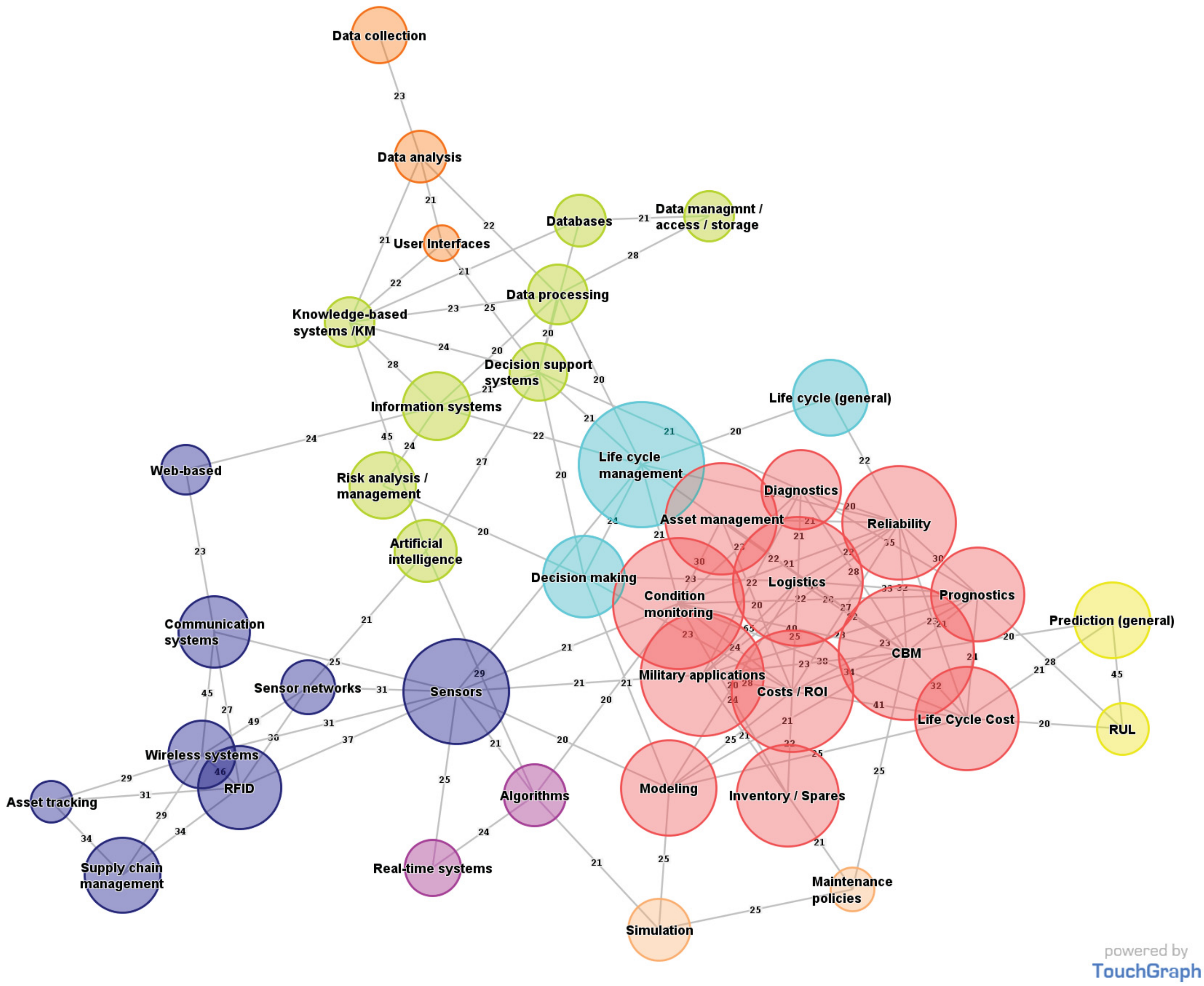

Figure 23. Subject Groups - Logistics Subset

Further analysis of the clusters related to information systems (yellow-green and dark orange in Figure 23) shows that recent research focus is centered on data collection, risk analysis, decision making and decision support systems as well as databases and information systems in general (Figure 24).

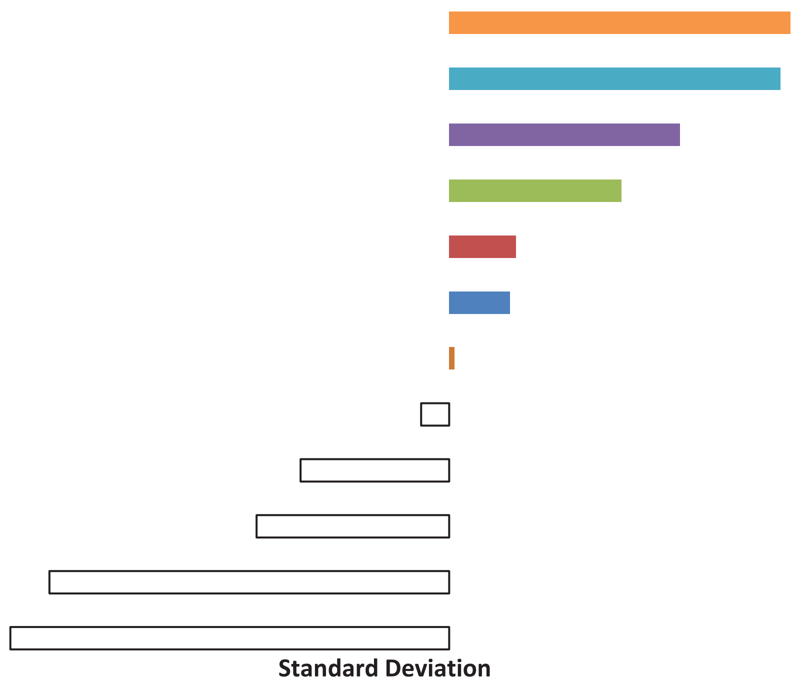

Figure 24. Relative Rate of Research Interest - Information Systems - Logistics Subset

A similar analysis was also performed on the clusters related to wireless systems, RFID, supply chain management and algorithms (dark blue and purple in Figure 23). This analysis (Figure 25 below) shows that recent attention is very much focused on the sensor-related technologies, with sensors, sensor networks, RFID and wireless systems showing the highest rates of research interest.

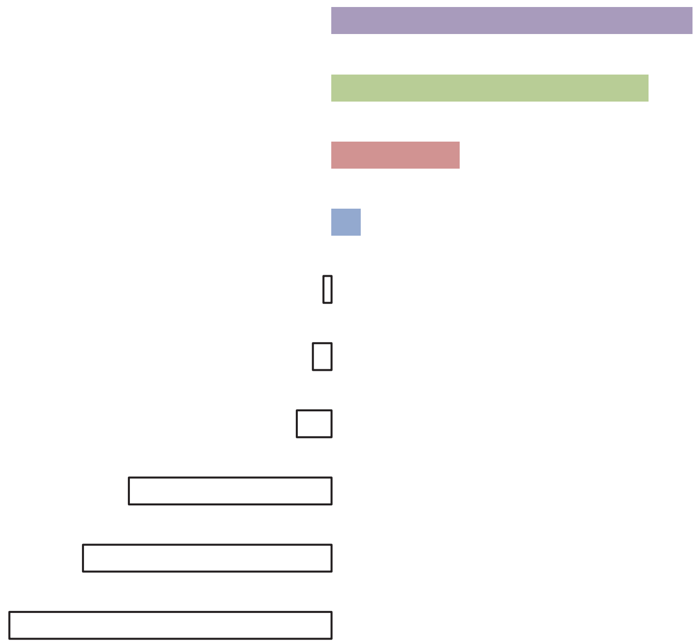

Figure 25. Relative Rate of Research Interest - Sensors, wireless and asset tracking clusters - Logistics Subset

The connection between maintenance and logistics is accomplished through logistics and asset tracking software. In the *Sense and Respond Logistics Technology Roadmap* of 2009, the authors point out that both diagnostic and prognostic software and algorithms are key enablers for the accurate determination, prediction and anticipation of logistics requirements of equipment maintenance, repair, refit and replacement (Cougaar Software 2009, 78). In addition, increased awareness, particularly if it is in real-time, of maintenance and repair requirements, contributes to a better situational awareness and can populate operational decision making tools (such as a Common Operating Picture or COP) for military planners:

> S&RL not only requires the best plans possible, but also that plans automatically update themselves as the situational picture evolves and it continually maintains alterative COAs [courses of action] and COSs [courses of support]. This applies not only to adapting to the battlespace as conditions change, but also to changes in maintenance and retrograde requirements as equipment experiences unusual wear and breakdowns.
>
> This capability allows decision makers to continually and automatically revise plans as situations change and to intervene only when those changes exceed defined parameters (Cougaar Software 2009, 154).

While the full integration of CBM information with COP tools may not be fully realized (Brady and Keating 2011), work is ongoing in this area and there is evidence of research into decision support tools in the CBM domain.

One of the conclusions of NRC-CISTI's 2010 report was that integration, interoperability and the improvement of the associated software and middleware for S&RL were seeing increased commercial and research attention, as observed by publication trends and a review of the market literature (Keating and Brady 2010). The sources reviewed for that project also noted that first steps of implementing S&RL frequently involve the rationalization and integration of multiple (legacy) logistical systems. Section 3.4 above discusses interoperability issues, which are generally addressed through the adoption of open standards, however, there is no one set of standards that are generally accepted and, in the case of RFID standards, there are sometimes hundreds available from which systems integrators must choose (Global RFID Forum for Standards 2008).

6.2 Military Autonomic Logistics Systems

Much of the literature on Autonomic Logistics is related to the Joint Strike Fighter (JSF) program, which is discussed in Section 6.2.1 below. Few other research publications describing AL system implementation or cost analysis could be found. Section 4.4 listed several cost-benefit studies of CBM system implementation but only one of those (Fischer 2011) took into account the effects and costs associated with autonomic logistics systems. The costs associated with logistics systems, particularly the costs of integrating with legacy logistical systems could be considerable and are important when planning any CBM implementation. A few other articles that could be useful for cost-benefits analysis that include logistics are highlighted below.

A research article by Khalak and Tierno describes a model that can be run to optimize lead times for repairs using corresponding supply chain costs (Khalak and Tierno 2006). Julka et al report on a series of case studies from the aerospace component logistics domain, where PHM information can be used for tactical planning and optimization of spare components logistics networks (Julka, Thirunavukkarasu et al. 2011). McGee et al. describe a simulation-based methodology for quantifying the effects of transportation options on shipping costs and operational readiness, which also takes into account mean-time-to-failure (MTTF) measures for aircraft components (McGee, Rossetti et al. 2005).

6.2.1 Autonomic Logistics for the Joint Strike Fighter (JSF)

The following section is based upon recent publications related to CBM and AL for the JSF program.

For the JSF (also known as the F-35 Lightning II), two areas in particular demonstrate the relationship between PHM and AL – the concept of Performance Based Logistics (PBL) and the Autonomic Logistics

systems themselves, often referred to as the Autonomic Logistics Global Sustainment (ALGS) systems and the Autonomic Logistics Information Systems (ALIS).
PBL is a program particular to the U.S. Department of Defense; however, given that the JSF is a multi-national program, the concept of PBL has far-reaching implications. PBL is a strategy "which capitalizes on integrated logistics chains and public/private partnerships. The cornerstone of PBL is the purchase of weapon system sustainment as an affordable, integrated package based on output measures such as availability, rather than input measures, such as parts and technical services"(Hess, Calvello, Frith et al. 2005) (Hess 2005b, 4). Essentially, PBL is a contractual-based approach that is based upon performance rather than the supply of platforms, parts and components. The vision is of a joint Government and Contractor team responsible for the provision of global technical support to the warfighter (Hess 2005a). PBL is sometimes referred to as performance-based contracting; an approach for buying set levels of performance, such as payment per flight hour, or availability contracting, referring to maintenance or support contracts for specific items of equipment (Frost & Sullivan 2006).

As noted by Frost & Sullivan, PBL arrangements are typically very complicated, with requirements in terms of manning and repair quality strictly defined. As well, PBL contracts often require interoperability between suppliers and the customer in terms of IT systems and processes. PBL contracts are similar to the U.K.'s Contractor Logistic Support (CLS) program, "in that contractors are penalized for failure to deliver services to the agreed standards. However, PBL does not involve the same kind of risk transfer from customer to contractor, as the CLS, and will usually not entail the same level of support. The customer will still retain the responsibility for the majority of tasks, with the contractor contributing only a certain amount" (Frost & Sullivan 2006, 8.6). It is the interoperability between suppliers and customers (government Defence departments) that makes PBL of particular importance for CBM and represents a change in the concept of operations (CONOPS) for logistics support of major platforms. Essentially, when a failure or impending failure is identified by the PHM system, the ALGS system is notified and sets off a chain of events that may include ordering spares, which is therefore connected to the suppliers' supply and asset tracking systems.

Interestingly, none of the articles reviewed for this section on the JSF (those discussing both PHM and AL) make any mention of asset tracking technologies. Once the supplier has delivered the spare parts to the warfighter, it is not clear who is then responsible for the tracking of the parts. Discussions of these challenges fall into the domain of Total Asset Visibility (TAV) systems and are generally not well covered in the CBM domain.

A recent article by McCollom and Brown makes the following observation:

> This last phase [of F-35 PHM system development] brings the advantages (and the inherent difficulties) of distributed operation and decision making across the user/provider/supplier areas of interest, and is generally driven by economics. The tendency to make locally optimal but system-wide sub-optimal economic decisions is managed through the evolving ground rules

> of the PBL environment. The deep involvement of suppliers, especially for those providing highly integrated or highly complex functions, is dependent upon new technology which is both necessary and highly sensitive. Add the further dimension of multiple service owners of the fleet, it will be apparent to the reader that this is an area that will be ripe for discussion for some time to come (McCollom and Brown 2011, 4).

The authors go on to mention that the F-35 PHM program has been focused primarily on near-term objectives in the areas of diagnostic and prognostic systems, leaving the full integration of AL with supplier systems as a challenge to be addressed further into the future. This assertion is also somewhat reflected in the data gathered for this project (see Figure 22), where there was an upsurge in interest in logistics topics until 2008, but there has been a significant drop in interest since then as the CBM community concentrates on PHM technologies rather than logistics.

Nevertheless, there is work ongoing on the logistics side, which brings us back to the discussion on cost-benefits analysis. If the interoperability with supplier systems is a question of economics, then cost-benefit studies that take into account both PHM costs and logistics costs are of critical importance. Hess et al describe several business case analysis (BCA) scenarios that take into consideration both prognostic and logistics metrics and tools for the JSF, which may be applicable to other system implementations as well (Hess, Calvello, and Frith 2005; Hess, Calvello, Frith et al. 2005).

As previously noted, data integration of legacy logistics and asset management systems is a key challenge for CBM implementation and one that must be faced by every nation for the JSF program since each country maintains its own unique set of legacy tools. A paper by Hagan and Walker describes the integration of JSF tools (ALIS) with legacy tools using a comparative analysis of data models used by the many different applications, databases and related systems (Hagan and Walker 2009). The challenge is to align the legacy commercial-off-the-shelf (COTS) and government-off-the-shelf (GOTS) data sources with the ALIS throughout the life cycle of the JSF. According to the authors, there is currently no tool to discover and compare data in the legacy system to the ALIS conceptual model. They propose and test two methods: a manual process that matches database fields from one system to another, which is effective but time consuming and expensive, and an automated process using conceptual modeling tools such as IBM's Rational Rose or Borland's Together Control Center. While this is only one article on the topic, further investigation of data integration methods and tools would be warranted for any AL implementation plan. Further information on the functionalities and methods of data transfer from the JSF's PHM system to ALIS is described in Brown, McCollom et al 2007 and may be useful as a starting point for investigations into ALIS data integration issues.

Lockheed Martin is the primary contractor for the JSF program and leads a consortium of companies supplying the JSF to defence departments around the world.[35] The following references may be useful for further information on the suppliers of the AL components for the JSF.

- Ottawa's Mxi Technologies is responsible for the Maintenix software and was awarded an extended contract for it in 2010.[36] According to a 2004 news release, "Maintenix will form the Commercial Maintenance Management System core of the F-35 JSF Autonomic Logistics Information System (ALIS) and will provide capabilities for asset management, maintenance program management, maintenance planning and scheduling, configuration control, and work execution."[37]
- IFS Defense was awarded a contract in 2005 for the development of the supply chain management component of the JSF.[38]
- ALD Group of Israel was contracted in 2003 for the development of the Failure Reporting Analysis and Corrective Action System (FRACAS), a sub-system of the ALIS software.[39] They also produce Integrated Logistics Systems.[40]
- The University of Southern California, Information Sciences Institute was awarded a contract to develop scheduling software to be used by the Marine Corps JSF program, with funds to be shared among Vanderbilt University and other contractors, including IDEA Services of Oakland, MD and Lloyd Lamont Design, Inc., of Herndon, VA.[41]

6.3 Commercial Systems and Industry Adoption

Apart from some general articles related to commercial airlines (Boen and Hansen 2007; Dupuy, Wesely et al. 2011; Rong, Zuo et al. 2010; Trebilcock 2011), no specific research projects or implementations of Autonomic Logistics involving both CBM functions and logistics or supply chain management in domains outside of the military could be identified. The following summary therefore concentrates only on RFID and asset tracking technologies for selected companies, with some general observations on RFID implementations in the retail industry. These references may be useful in preparing for AL implementations for the Canadian Forces as specific implementation challenges are discussed.

[35] Lockheed Martin's ALIS website is: http://www.lockheedmartin.com/us/products/f35/f35-sustainment/alis.html
[36] http://www.prweb.com/releases/LockheedMartion/0410/prweb3926894.htm
[37] http://www.businesswire.com/news/home/20040210005118/en/Lockheed-Martin-Selects-Mxis-Maintenix-Software-F-35
[38] http://www.f-16.net/news_article1287.html
[39] http://www.favoweb.com/pdf/pr_favoweb_lm.pdf
[40] http://www.aldservice.com/en/reliability-services/ils-lcc.html
[41] http://www3.isi.edu/print/about-news_story.htm?s=63

6.3.1 Wal-Mart and RFID for the Retail Industry

Wal-Mart issued a policy in 2003 that by January 1, 2005 their top 100 suppliers in the U.S. would have to begin using RFID technology to track goods both en route to Wal-Mart distribution centres and within their stores. This policy met with some very negative responses from the industry and up until 2008, the move was being described as "a failure" (Hayes 2008), that suppliers were complaining that the cost of serving Wal-Mart went up (Pinpointing the ROI in RFID 2007) and that some companies are surviving on "slim profit margins" due to the mandate (Weier 2007). Nevertheless, Wal-Mart persevered and began to see that RFID reduced their out-of-stocks by 21% (Hardgrave, Langford et al. 2008) and lead to quicker restocking of shelves, resulting in increased sales for some suppliers (S.S. 2007).

It was expected that Wal-Mart's mandate would lead to greater uptake of RFID technologies in the retail industry, but some analysts have noted that "very little of that mandate has become a consolidated industry practice"(Balocco, Miragliotta et al. 2011). On the other hand, there is increased adoption of RFID for some major retailers, including Metro AG of Germany, Tesco in the U.K., Marks & Spencer, Target, Best Buy, and many others. The following is a summary of the process-related benefits of RFID for the retail supply chain, compiled from two sources (Brown 2007; Riemenschneider, Hardgrave et al. 2007):

- Reduced out-of-stocks
- Reduction of manual orders, which are time consuming and expensive
- Improved management of restocking during promotions, leading to increased sales
- More efficient receiving processes in distribution centres, including electronic proof of delivery
- Better asset and fleet management of delivery vehicles
- Complete life cycle tracking leading to better predictions and forecasting of demand and stocking levels
- Improved visibility of orders at all stages of the supply (on shelves, in distribution, on order, in transit) leads to more cost-effective purchasing and avoids overstocks
- Increased collaboration among all players in the supply chain, leads to better sales forecasting, order generation and delivery execution
- Evolution to a new business practice called 'Vendor Managed Inventory (VMI)', in which the supplier monitors demand and stock levels which helps them to improve production planning, reduce inventory, improve inventory turnover and improve stock availability.

VMI is very similar to the PBL concept, in which asset visibility and logistics information systems are shared with suppliers, who may be contractually responsible for maintenance and supply of defence platforms, including inventory and spares.

6.3.2 United Parcel Service (UPS) and FedEx

Both UPS and FedEx have made announcements of several RFID pilot studies over the past few years. As two of the world's largest package delivery companies, their adoption of RFID has the potential to significantly influence the industry and uptake of the technology.

While UPS appears to be pushing RFID solutions on its website[42] it is not clear to what extent they have adopted RFID technologies for the delivery of service. In 2005 it was announced that UPS decided to delay roll-out of RFID technology for small packages, which account for 90% of its business (Saran 2005). However, a 2004 report mentions that UPS adopted RFID tags for their trucks so that readers monitor when vehicles arrive at and depart from logistics facilities, taking the burden off drivers to sign in and out (Bednarz 2004). In a 2005 white paper (UPS Supply Chain Solutions 2005), they outline the pitfalls of RFID adoption, which include the following:

- Costs – of the tags themselves and the related components, such as software, systems integration and process redesign
- Tag readability – some technical issues remained to be resolved (as of 2005)
- Data management issues such as what information to capture and how to use it
- Data ownership and sharing – the willingness of participants in the supply chain can be a challenge
- Too many RFID standards
- Business process changes – process automation through RFID will require new work methods, performance measures, and organizational changes
- Privacy concerns, particularly from consumers, who do not want themselves or the items they purchase to be tracked once they own them

FedEx has been showing interest in RFID technology since 2001 when they announced a pilot study to use RFID tags to prevent lost car keys (Burnell 2001). In 2005 FedEx cited the cost of RFID and its existing investment in barcode technology as their biggest challenge to adoption, but that they would start off with RFID acting as a supplemental offering with some suppliers (Saran 2005). In 2006 they also announced a partnership with Boeing Co. to test RFID tags to improve parts visibility for aircraft parts (Boeing and FedEx test active RFID 2006). In a 2009 interview, Vice-President and Chief Information Officer of FedEx provided an overview of technologies being tested and developed by FedEx (Hayes 2008), which included active RFID tags connected to the Internet. He also mentioned that they are piloting sensors to monitor temperature and vibration using embedded sensors, so their use of RFID and sensors appears to be going beyond asset tracking to include elements of CBM. The extent of FedEx's actual implementations is not entirely clear but may be worth further investigation.

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[42] See their library of case studies and white papers at: http://www.ups-scs.com/solutions/library.html

7 MAJOR PLAYERS

7.1 Organizations

The major players in the following section are listed according to numbers of publications and patents. In addition to these players, producers of analytical software are also important and are listed as CBM systems vendors in section 3.3

	Condition Monitoring	Sensors	Health Assessment	Analytics	Communi-cations	Data manage-ment	Decision support	User Interfaces
Harbin Institute of Technology, China	63	34	29	43	6	9	15	1
U.S. Air Force Research Laboratory (AFRL), Wright-Patterson AFB, OH, USA	33	18	31	22	2	7	11	
Impact Technologies, Rochester, NY, USA	31	13	36	43	10	12	9	1
University of California, San Diego, CA, USA	29	27	21	24	8	5	4	
Georgia Institute of Technology, Atlanta, GA, USA	29	19	24	24	6	4	4	
Nanjing University of Aeronautics and Astronautics (NUAA), China	29	18	28	21	7	2	9	
Pennsylvania State University, University Park, PA, USA	28	20	20	18	8	6	8	2
Northwestern Polytechnical University, Xi'an, China	26	10	26	23	5	6	5	
University of Sheffield, United Kingdom	25	11	25	14	4	5	2	
University of Maryland, College Park, MD, USA	23	9	28	23	8	6	13	
University of South Carolina, Columbia, SC, USA	22	22	15	6	5	5	1	1
University of Tokyo, Japan	21	29	17	8	3	3		
University of Michigan, Ann Arbor, MI, USA	20	17	12	17	15	7	7	
Shanghai Jiaotong University, China	19		24	23	2	3	15	1
NASA Glenn Research Center, Cleveland, OH, USA	19	6	24	16	4	4	4	1
Beihang University, Beijing, China	18	4	30	31	1	8	11	
NASA Ames Research Center, Moffett Field, CA, USA	18	10	29	26	3	11	6	2
Dalian University of Technology, China	17	19	13	10	4	1	2	
Beijing University of Aeronautics and Astronautics (BUAA), China	15	1	19	19	3	6	7	1
NASA Langley Research Center, Hampton, VA, USA	14	14	11	14	5	2	1	

Figure 26. Major Players - Number of records for DoD Categories, 2006-2011

Figure 26 shows the 20 players from the scientific literature with the highest number of total publications in each of the major DoD technology categories. The numbers and circles represent how many articles each organization has in each category, which illustrates their areas of focus. Further details on each of these players, including top authors, co-authoring institutions and areas of expertise, are found in Appendix 10.5.

Figure 27 shows all Canadian players with five or more publications, with the corresponding numbers of publications for each DoD category.

	Condition Monitoring	Sensors	Health Assessment	Analytics	Communi-cations	Data management	Decision support
University of Toronto, ON	13	2	10	10	1	2	7
Defence R&D Canada (DRDC), Ottawa, ON	11	13	8	2	2	1	
Concordia University, Montreal, QC	11	2	7	11			6
National Research Council Canada, Ottawa, ON	7	7	9	7		4	2
Ecole Polytechnique de Montreal, QC	7		7	8		4	1
National Research Council Canada, Boucherville, QC	6	6	4	1			
University of Manitoba, Winnipeg, MB	5	3	2	3	1		1
McGill University, Montreal, QC	5	5	3	2	1		2
University of Waterloo, ON	4	1	2	1	2		
Dalhousie University, Halifax, NS	4	3	3	2	1	1	1
University of Alberta, Edmonton, AB	3	1	2	5			1
Ecole de Technologie Supérieure, Montreal, QC	3	1	2	4	1		1
University of Ottawa, ON	2	5	3	2			2

Figure 27. Canadian Players with 5 or More Publications, 2006-2011

The top patent assignees over all are illustrated in Figure 28. Here we see a strong showing by automotive companies as well as well-known aircraft and engine manufacturers. As previously mentioned, the strong showing of automotive vendors reflects the high presence of vehicle telematics applications and tire condition monitoring systems in the patents, both of which are relatively mature domains.

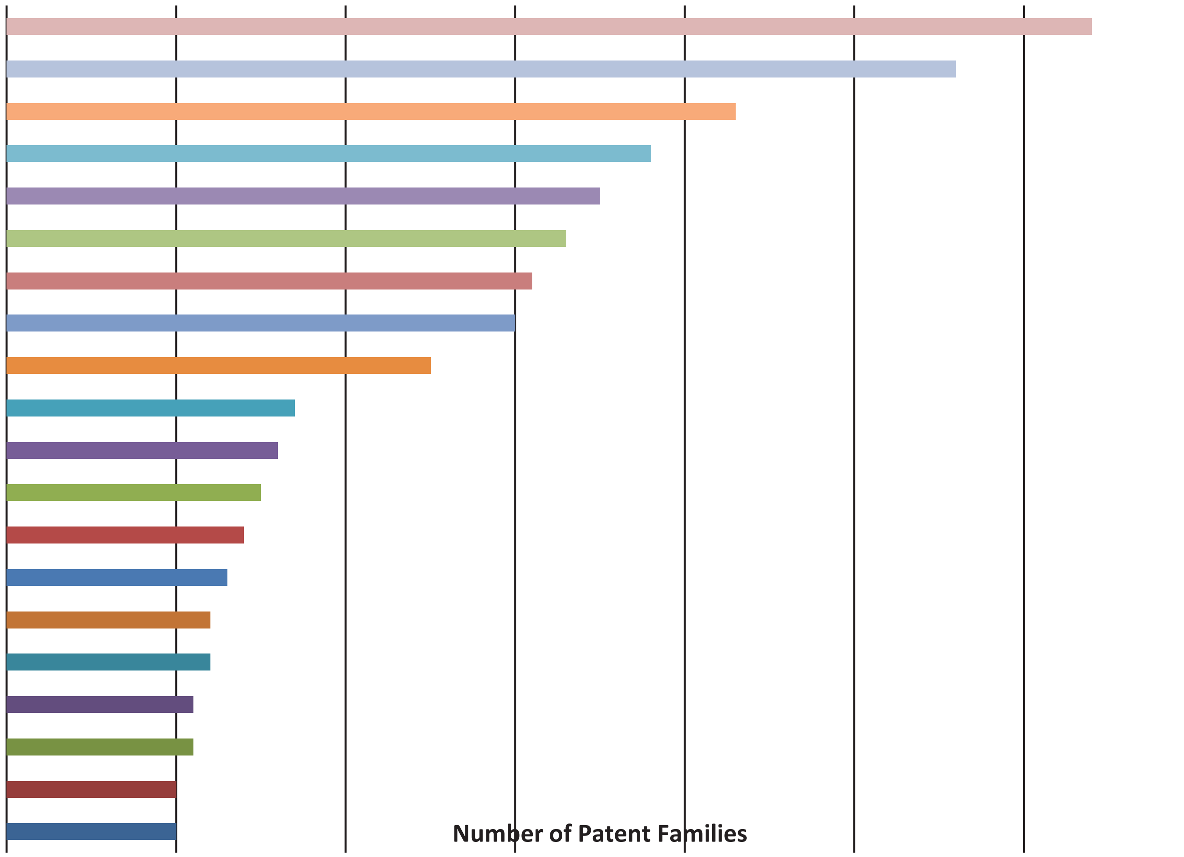

Figure 28. Patent Assignees with 10 or more Patents, 1990-2011

Figure 29 below shows the top patent assignees from the non-automotive dataset and the subject areas prominent in their patents. There remain a few automotive manufacturers in this list, however their patents in this dataset do generally reflect condition monitoring technologies and are not strictly related to vehicle telematics or tire condition monitoring.

Assignee name	Data processing	Test / diagnostics of vehicles	Vehicle monitoring	Control systems	Communication systems	Vehicle electric circuits	Aircraft maintenance/ repair	Aircraft indicators	Alarms, notification	Data access	Electrical testing/ fault detection	Error detection/ monitoring	Monitoring machines, excl vehicles	Testing of structures	Wireless signalling
BOEING	25	9	5	7			6	5	3					3	
HONEYWELL	22	4	8	9			3	3	3	3		5	4		
GENERAL MOTORS	15	10		3	3	4					4				3
GENERAL ELECTRIC	10		7	5				4	3	5	6	6			
SPX CORP	8	7			5										
AIRBUS	7	3		6	3		6	9	7					6	
BOSCH GMBH	6	6	6		3	5						3			
DAIMLER CHRYSLER	5	5	4	4	3	6						3			3
EATON CORP	5		3								5				
FORD GLOBAL	5	4			4										
LOCKHEED MARTIN	5														
DENSO	4	7		3	6	5									
SNAP ON TECH	4	6	4		5										
TOYOTA MOTOR	3	5													
HITACHI				3											

Figure 29. Top Patent Assignees - Non-Automotive Applications, 1990-2011

7.2 Authors

Table 3 below lists the 15 authors with the highest number of publications in the master dataset of 4,394 records. Table 4 lists the Canadian authors with five or more publications. Further details on all these authors are provided in Appendix 10.5.

Table 3. Top Authors – International, 2006-2011

Author Name	# Publications
Pecht, Michael University of Maryland, College Park, USA	45
Goebel, Kai F., NASA Ames Research Center, Moffett Field, CA, USA	35
Takeda, Nobuo University of Tokyo, Japan	25
Ou, JinPing Harbin Institute of Technology, China	24
Adams, Douglas E., Purdue University, West Lafayette, IN, USA	23
Bechhoefer, Eric Goodrich Corporation, Vergennes, VT, United States	22
Roemer, Micheal J., Impact Technologies, Rochester, NY, USA	22
Byington, Carl S., Impact Technologies, Rochester, NY, USA	21
Vachtsevanos, George J., Georgia Institute of Technology, Atlanta, GA, USA	21
Worden, Keith, University of Sheffield, United Kingdom	21
Farrar, Charles R., Los Alamos National Laboratory, NM, USA	19
Giurgiutiu, Victor University of South Carolina, Columbia, SC, USA	18
Inman, Daniel J., Virginia Polytechnic Institute and State University, Blacksburg, VA, USA	18

Table 4. Top Authors – Canada, 2006-2011

Author	# Publications
Mrad, Nezih Defence R&D Canada (DRDC), Ottawa, ON	16
Jardine, A. K. S., University of Toronto, ON	10
Yacout, Soumaya Ecole Polytechnique de Montreal, QC	10
Makis, Viliam University of Toronto, ON	9
Banjevic, D., University of Toronto, ON	8
Tian, Zhigang Concordia University, Montreal, QC	7
Ghasemi, Alireza Ecole Polytechnique de Montreal, QC	6
Jen, C.-K. National Research Council Canada, Boucherville, QC	6
Kobayashi, M. National Research Council Canada, Boucherville, QC	6
Ouali, M. Salah Ecole Polytechnique de Montreal, QC	6

8 CONCLUSIONS

The DoD *CBM+ Guidebook* (Deputy Under Secretary of Defense for Logistics and Materiel Readiness 2008) provides practical guidance on implementing a CBM+ program. Their recommendations require consideration of the business and management implications as well as the technical aspects. While this guidebook is designed specifically for the U.S. military, it could be studied and adapted to the Canadian Forces context. The companion document on conducting business case analyses (OSD CBM+ Action Group 2010) should be read in conjunction with the DoD *CBM+Guidebook*.

A critical element to developing a Canadian Forces policy will be to decide on the cost-benefit analyses and models that can be used to determine the economic feasibility of CBM implementation alternatives. Many examples exist and could be adapted for this purpose – some of which are outlined in the benefits section above. Decisions on the parameters to include in the cost benefit models will have to be made. Leao et al. say that CBA "must always be developed together with a technical analysis. This analysis provides the technical feasibility of performing PHM for each specific aircraft system or component, and yields estimates on how effective the PHM algorithms may be for a certain application"(Leao, Fitzgibbon et al. 2008, 9).

The following are NRC-CISTI recommendations for a DRDC case study project:

- Conduct a pilot study in which good historical data on key metrics already exists– such as maintenance records, usage data and financial/cost records.
- Concentrate on key areas where the Canadian Forces client has already identified a need to reduce maintenance costs and/or spare parts costs.
- Execute both an engineering study on prognostics effectiveness and a cost-effectiveness study in tandem and be sure to include logistics costs and metrics in the study.
- Involve both maintenance engineers and cost accounting/financial modeling experts in the pilot study.
- Use a software tool that can model different CBM scenarios and that provides sound cost-benefits analysis, based on the literature cited in this report.
- Consult the list of references in appendix 10.3.1 on conducting cost-benefit studies.

Based upon the sources reviewed for this study, the benefits of CBM are substantial and could represent significant cost-efficiencies in the long-term. However, short term benefits are difficult to realize since initial investments in acquisition and installment costs are high. In addition, careful consideration must be paid to data integration with legacy systems, particularly supply chain management and logistics systems. Work on the JSF is advancing development of PHM methods as well as the related logistics systems, and is an important area to monitor as many of the lessons learned for the JSF program could be applied to retrofitting legacy platforms.

This study provides a broad overview to enable DRDC to make recommendations on a way forward for the Canadian Forces but there are some issues that may require further study. The authors of this report recommend that DRDC continue to monitor developments in the following areas:

- The development and adoption of CBM-related standards. It will be interesting to see which ones emerge as those that are generally accepted. Standards for sensor and data interoperability are particularly important, as are RFID standards.
- Seek out other studies on data integration of CBM systems, AL systems and legacy systems for various military organizations.
- Monitor uptake of RFID and asset tracking technologies in other industries, particularly retail and transport. High uptake of the VMI concept could result in dramatic changes to business practices for supply chain management.
- Given that AL issues are not widely discussed in the CBM literature, an increase in interest in AL in that community could indicate that AL is maturing and that solutions are closer to fruition.

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10 APPENDICES

10.1 Attachments

The following files are provided as attachments to this report:

Filename	Description
9420 CBM Top300 Cluster Map – Figure 3.png	This is the complete map for which Figure 3 is a detail view
9420 CBM Sensors Top300 Cluster Map – Figure 7.png	This is the complete map for which Figure 7 is a detail view
9420 CBM Systems.xlsx	Provides details and links on prognostic and diagnostic software for CBM systems, with a focus on vendors providing tools for military organizations.

10.2 Methodology

10.2.1 Searches

Several searches were conducted in various databases, particularly *INSPEC, Ei-Compendex, Scopus*, *NTIS* and *NATO Scientific Publications*. Results were limited to the last 6 years (2006-2011). Searches were made within the dataset to weed out any false hits on human health monitoring. The final dataset contained 4,394 unique publications.

The table below shows groups of concepts, which were combined in multiple variations using database-specific syntax to obtain relevant references. The search combined these sets in several variations and some strings were limited to title, subject heading or keywords for greater precision.

Search concepts:

1: CBM/PHM	2: CBM/PHM, qualified	3: Vehicles/Military domain
Prognostics and health management Diagnostics and health management Condition Based Maintenance Structural Health Monitoring	DPHM PHM CBM SHM IVHM HUM RCM condition monitoring health monitoring health management health and usage monitoring predictive diagnostics reliability centered maintenance damage management maintainability tracking maintainability analysis	Aircraft Helicopters Rotorcraft Ships Vehicles Military National security Homeland security Armed Forces Air Force Navy Army Soldiers Weapons

A similar search strategy was applied in the FamPat worldwide patents database from Questel-Orbit. In addition, specialized searches using patent classifications were performed, as well as searches on companies known to be active in the domain, combined with terms from Set 2 above. More than 1,600 patent families were retrieved, but were manually weeded to exclude patents on traffic condition monitoring and vehicle telematics systems not related to condition monitoring. A total of 1,204 patent families were analysed.

10.2.2 Analysis

All references were downloaded into VantagePoint software for analysis. VantagePoint enables the creation of various groupings, matrices, graphs, cross-correlations and statistical analyses to analyze the data and draw conclusions about topics and subtopics and to profile the activities of the major players.

Author names and author affiliations were cleaned to harmonize variant forms and spellings and group together departments from the same institutions.

Keywords, identifiers (usually author-supplied keywords), descriptors, and subject headings were merged together to facilitate subject analysis, resulting in over 9,000 terms. These terms were cleaned and edited to harmonize variant spellings, acronyms and similar meanings. These terms were then grouped into thematic categories for further analysis and discussion.

Growth Rate Analysis using Z-scores Normalization

The percentage (%) of total records is a measure of research interest attracted by a subject area. In order to quantify chronological changes in this measure, the growth rate of the numbers of publications divided by total publications is plotted over time and then slopes are calculated based on linear regression of the lines showing rate of change in the % of total records and then normalized to z-scores to enable comparison between the subject areas. Z-scores are normalized values of a dataset. The normalization process eliminates the unit of measurement by transforming the dataset into new scores with a mean of zero (0) and a standard deviation of one (1). Each z-score indicates the number of standard deviations a value is above or below the mean.

For example, the rate of change of the sensor technologies are plotted as shown in the Figure 30 below, using 2006 as the base year (equal to 1). The slopes of these lines are calculated based on linear regression of the lines, and then normalized to z-scores and plotted in a bar graph (Figure 31).

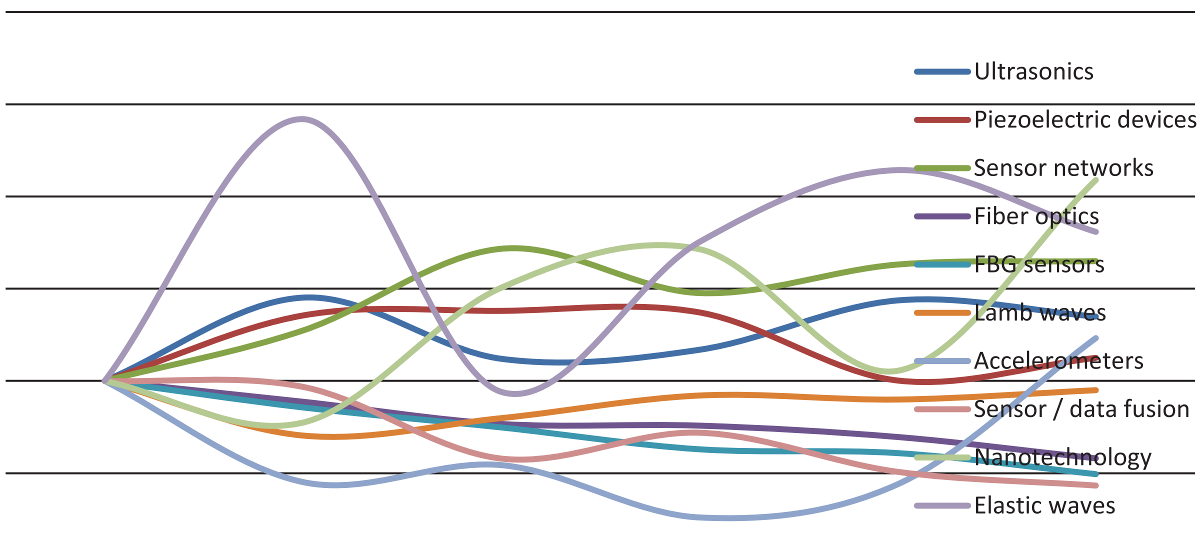

Figure 30. Rate of change in % of total publications - Sensor Technologies

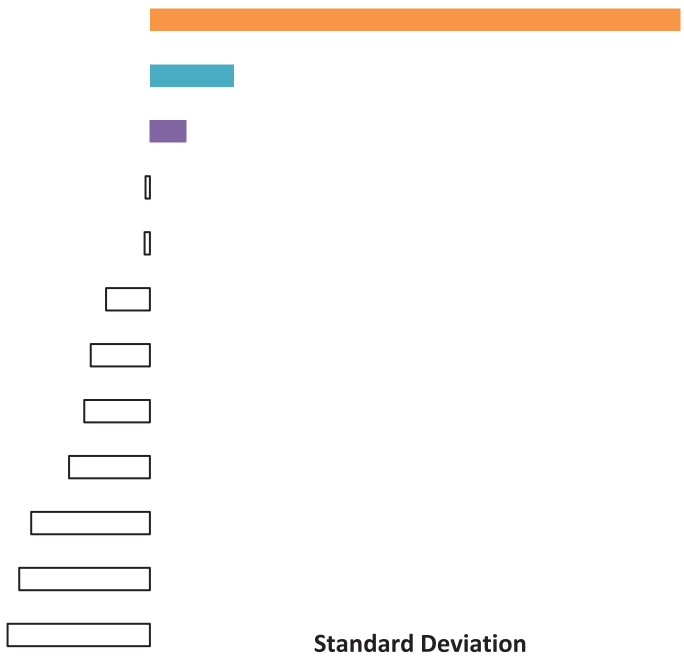

Figure 291. Relative Rate of Research Interest - Sensor Technologies

10.2.3 Sources Consulted

Scientific & Technical Literature databases:

- *Scopus* (accessed via CISTI license)
- *INSPEC* (accessed via CISTI license)
- *EiCompendex* (accessed via CISTI license)
- *NTIS* (accessed via Dialog online search service)
- DTIC Online – *Technical Publications* http://www.dtic.mil/dtic/search/tr/tr.html
- NATO Research & Technology Organisation - *Scientific Publications* http://www.rta.nato.int/abstracts.aspx
- DSTO *Publications Online* http://dspace.dsto.defence.gov.au/dspace/

Market and Trade Literature:

- Frost & Sullivan (accessed via CISTI license)

Other Sources :

- Command and Control Research Program (CCRP) website http://www.dodccrp.org/

10.3 Recommended Sources

10.3.1 Guidelines for Cost-Benefits Analysis

The following references are good sources for guidance on conducting a cost-benefits analysis for CBM implementation.

Banks, Jeffrey, and John Merenich. 2007. Cost Benefit Analysis for Asset Health Management Technology. In *53rd Annual Reliability and Maintainability Symposium (RAMS 2007)*. Orlando, FL: IEEE.

Byer, Bob, Andy Hess, et al. 2001. Writing a Convincing Cost Benefit Analysis to Substantiate Autonomic Logistics. *Proceedings IEEE Aerospace Conference* 6:3095-3103.

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Sun, Bo, Shengkui Zeng, et al. 2010. Benefits Analysis of Prognostics in Systems. In *Prognostics & System Health Management Conference*. Macau, China: IEEE.

10.3.2 Lessons Learned

In answer to Key Question #11: "*What are the published lessons learned from the battle field or other implementations of CBM, AL, and SRL in a military setting?*", the following references have been gathered and are recommended for detailed study of actual CBM or logistic system implementations in Afghanistan, Iraq, Pakistan, and Kuwait.

A similar list of references was provided for the CISTI project on Sense & Respond Logistics (Keating and Brady 2010). The list below provides a brief update to that bibliography, so references directly related to Sense & Respond Logistics are not provided here; instead the reader should refer to the 2010 report.

AVT-144 Technical Team. 2011. ***Enhanced Aircraft Platform Availability through Advanced Maintenance Concepts and Technologies:*** *The Report of an investigation by the AVT-144 Technical Team, which includes information contributed during the Workshop documented in RTO-MP-AVT-144.* NATO Research and Technology Organisation. www.dtic.mil/dtic/tr/fulltext/u2/a545816.pdf
Abstract: This report identifies maintenance/support management and equipment technologies which can improve aircraft platform availability. It contains information from a Workshop of invited specialists held in October 2006 (RTO-MP-AVT-144) and separate research by the AVT-144 Technical Team. Aircraft availability is a key component of military capability and an important measure of the readiness and effectiveness of a force. For military effect, high availability on the flight line must be accompanied by continued availability throughout a mission profile, i.e. mission reliability. During deployments and expeditions, a higher than average availability is usually desired. To maximize availability it is necessary to minimize the need for maintenance and the associated downtime. Attrition due to battle damage must also be minimized. The design and management of an aircraft and its maintenance/support occurs in the context of many competing priorities for the available development and operating funds. Therefore, it is important that a systematic approach is followed to achieve an acceptable balance between availability and other force requirements. The report describes how advanced systems engineering and business management processes and advanced aircraft and support equipment technologies can be applied in an integrated manner to achieve this goal.
Notes: 5.12.4 RCM **and "Condition-Based Maintenance (CBM)** [See page 5-36]
6.11.4 **The Lessons Learnt About Battle Damage ... 2-4 UK Joint Battlefield Support Helicopter** [See page 6-123]

Bochenek, Grace, Kirk C.Benson, and Vic S.Ramdass. 2011**. "What's on the horizon? Future capabilities through the logistics lens.**" Paper presented at the 2011 Tactical Wheeled Vehicles Conference, 6-8 Feb 2011, Monterey, CA. http://www.dtic.mil/ndia/2011tactical/MondayBochenek.pdf

Brown, Joel and Varian, Paul. 2008. **"Joint Robotics Program."** Paper presented at 5th Annual Acquisition Research Symposium of the Naval Postgraduate School, 14-15 May 2008. http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ada493944.pdf&Location=U2&doc=GetTRDoc.pdf
Abstract: Sun Tzu wrote first about the importance of logistics over two thousand years ago, followed by Von Clauswitz 150 years ago. Much like human transportation history evolution -- beginning first with people walking or running from point a to point b, followed by thousands of years being transported by real horse power, then automobiles, airplanes, and rockets -- logistics too has progressed over the years: focusing first on Mass-based Supply, then Just-in-

Time Supply Chain Management, and now on Sense and Respond logistics. The Robotic Systems Joint Project Office (RSJPO), an Army-Marine Corps effort that supplies various robots to the AORs of Iraq and Afghanistan, has also evolved through the three logistics methods. During each approach, many positive benefits were discovered. Along with those benefits, there were and are still today challenges to be confronted and overcome. The Robotics Program's experience and lessons learned since it began real time theater support in 2003 can aid all logistics programs by exemplifying the better ways to provide the best logistics with the knowledge, skills, and tools available today. All logistics functions, as shown by the Robotics Program, can be provided incredibly fast, quite inexpensively, and with superior quality and customer satisfaction.

Cannon, C. K. 2006. ***Logistics Modernization: The Answer to Attrition Logistics***. Quantico, VA: United States Marine Corps, Command and Staff College, Marine Corps University
http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA504572
Abstract: Advancements in tactics, equipment, and technology have been utilized extensively within the aviation combat element (ACE) and ground combat element (GCE) over the last two decades to dramatically increase their range and lethality on the battlefield. However, commensurate improvements have not occurred within the Marine air ground task force's (MAGTF) combat service support element (CSSE), which has resulted in a capabilities gap between the fast moving, highly efficient 'teeth' of the MAGTF, and its antiquated and unresponsive 'tail.' The inability of the CSSE, with its capabilities rooted in the tactics and technology inherited from its 'attrition warfare' oriented predecessors, to support the highly mobile and maneuver centric warfighters of the ACE and GCE was clearly demonstrated in Operation Iraqi Freedom I (OIF I). Lack of a well defined command and control (C2) architecture, reliance on antiquated and non-interoperable supply and maintenance systems, lack of total asset visibility (TAV) and in-transit visibility (ITV) within the MAGTF, and the radically different task organization adopted by the CSSE in theater, all contributed to its inability to provide responsive combat service support (CSS) to the MAGTF's maneuver forces.

Caseres, L. and Jakab, M.A. 2010. **"Field deployment of wireless sensors to monitor coating degradation and environmental corrosivity."** Paper presented at NACE - International Corrosion Conference Series, San Antonio, Texas, 14-18 March 2010.
http://www.onepetro.org/mslib/servlet/onepetropreview?id=NACE-10175
Abstract: Impedance based coating degradation, wetness, and cumulative damage sensors were deployed in several US Marine Corps bases. The sensors were placed inside dehumidified storage buildings and on ground vehicles stored outdoors to monitor the performance of corrosion preventive compounds (CPCs), and the severity of the environment as a function of time. The sensors were able to record coating integrity information real-time, and transmit this information remotely from a set of readers and base stations to a web-based portal for convenient monitoring and analysis. The sensor data were in agreement with visual observation

of the sensor surface. The sensor information indicated vast differences in corrosivity depending on location, environment/seasonal conditions, storage location and location on vehicle. The least severe condition monitored was the dehumidified storage in Camp Lejeune, where the assets were protected from precipitation and condensation, and the relative humidity levels did not exceed 60%. The most severe conditions were found on vehicles stored on-lot, where coatings applied to boldly exposed surfaces were completely degraded and exposed elements were severely corroded. The CPCs were, however, effective in case of crevices, even under the most severe environmental conditions. In this paper, the results of the 2-year program are summarized.

Figueiredo, E. 2010. "**Autoregressive modeling with state-space embedding vectors for damage detection under operational variability**." *International Journal of Engineering Science* 48 (10): 822-834.
Abstract: A nonlinear time series analysis is presented to detect damage in systems under varying operational and environmental conditions. This paper summarizes the use of a state-space reconstruction to infer the geometrical structure of a deterministic dynamical system from observed time series of the system response at multiple locations. The unique contribution of this paper is using a Multivariate Autoregressive (MAR) model of a baseline health condition to predict the state space, where the model encodes the embedding vectors rather than scalar time series. A hypothesis test is established that the MAR model will fail to predict future response if damage is present in the test condition, and this test is investigated for robustness in the context of operational and environmental variability (nondamage-related events). The applicability of this approach is demonstrated using multi-channel acceleration time series from a base-excited three-story building structure tested in laboratory environment. Under the assumption that many real-word damage modes induce transitions from linear to nonlinear response in a system, damage is simulated by a bumper mechanism that creates a repetitive, impact-type nonlinearity. Operational and environmental variations are simulated by changing stiffness and mass conditions, based on the assumption that these sources of variability usually manifest themselves as linear effects on measured data.

Hendry, M. L., Zekas, B. M. 2008. **"U.S. Navy experience with SSS (synchro-self-shifting) clutches."** *Proceedings of the ASME Turbo Expo: Power for Land, Sea, and Air* 7: 463-474.
Abstract: The U.S. Navy has nearly forty years of experience using SSS (Synchro-Self-Shifting) Clutches in main reduction gears of gas-turbine-driven ships and propulsion systems with combinations of gas turbines and diesel engines or electric motors, and in steam-turbine propulsion plants for use with electric motor drives. Over 900 SSS Clutches have been installed in fourteen different classes of U.S. Navy ships, some in service for over thirty years. This paper presents a brief overview of the principle SSS Clutch design features and the operating experience in naval propulsion systems worldwide, including operation in various propulsion plants such as controllable reversible pitch (CRP) propellers, fixed-pitch propellers (FPP), etc.

The paper will also focus on SSS Clutch designs for specific U.S. Navy applications and installations, U.S. Navy experience, and design changes and improvements that have been implemented since the initial U.S. Navy use of SSS Clutches. Detailed metric (statistical) data, used by the U.S. Navy to evaluate equipment performance and life cycle costs, such as mean time between failure (MTBF), mean time to repair (MTTR), mean logistics delay time (MLDT), and operational availability (Ao) will be used to support experience. In-service experience and failure modes will also be explained as well as findings from the evaluation of clutches that have been subjected to extreme operation/incidents such as overspeed, overtorque, high shock blast, and flood damage. The final part of the paper will discuss current/future applications on U.S. Navy vessels such as the LHD-8, LCS and others; and how the design/features of those SSS Clutch designs will satisfy the operational, reliability, and maintainability requirements established for each ship platform. The metrics and lessons learned will be shown to be equally applicable to clutches for critical auxiliary drive applications such as naval gas turbine generator starting and naval steam turbine generator turning gear systems and how these metrics and lessons learned are being applied for current and future U.S. Navy ship systems.

Inspector General. 2010. ***Repair and Maintenance Contracts for Aircraft Supporting Coalition Forces in Afghanistan, Iraq, and Kuwait.*** Washington, DC: Department of Defense. http://www.dodig.mil/audit/reports/fy10/10-047.pdf
Abstract: We determined whether equipment repair and maintenance contracts for aircraft supporting coalition forces in Afghanistan, Iraq, and Kuwait were effective. To determine effectiveness, we evaluated the efficiency of oversight controls and adequacy of training programs to ensure that DOD received services it paid for. Specifically, we reviewed four task orders awarded by the Air Force Contract Field Team (CFT) Program for over $900 million. Although this is an Air Force program, the Army is the primary customer.

Jackson, J. W. 2007. "**Viability of the Air Mobility Command Pure Pallet Program for US Army Reparable Retrograde Shipments**." Master's Thesis, U.S. Air Force Institute of Technology (AFIT), Wright-Patterson AFB, OH, USA. http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA466669
Abstract: Last year, Congress approved $17.1 billion dollars, an increase of $4 billion dollars more than originally was requested by the Bush Administration, for US Army vehicles to be repaired or replaced (commonly referred to as reset) as a result of military operations in Iraq and Afghanistan. A large portion of the repair workload falls upon the Army depots in Anniston and Red River in Texarkana, Texas and must rely on the DOD transportation system for air and surface movement of retrograde cargo deemed serviceable and unserviceable to fill requisitions and backorders for entry into the national supply inventory. Headquarters Air Mobility Command developed an initiative for distribution to the US Central Command to allow supply requisition shipments to accumulate based on customer defined delivery timelines to a single unit destination to eliminate the need of mixed destinations on a single pallet, thereby avoiding intermediate handling and increase in-transit visibility. This research viewed the depot and the

item managers as the customers due to the value they collectively add in equipment repairs and how retro grade is directed to meet the needs of the end user. Subject matter experts from Army Materiel Command provided their inputs through a series of focused interviews to calculate their value placed on transportation system and convergence with a cost comparison of the accumulation principles of the AMC pure pallet program. The results indicated that the AMC pure pallet program was not a viable option due to conflicts with customer requirements, high variability in the volume of retrograde generated to successfully utilize this option despite the savings in using consolidated shipments.

Law K., Todd, K, Wogoman, C. 2008. **"On-wing engine performance monitoring and alarming."** Paper presented at American Helicopter Society International - AHS International Condition Based Maintenance Specialists Meeting.
Abstract: Health and Usage Monitoring Systems (HUMS) have revolutionized many aspects of aircraft operation, functional check flight evolutions, and maintainability, and have inherently provided increased safety margin; however, few have capitalized on on-wing parameter alarming, including engine performance. Due to the increased frequency of operating our military aircraft in such locations as Afghanistan, Iraq, and aboard naval vessels where aircraft engines are inherently subjected to the most austere environments in terms of sand and salt water, accelerated engine performance degradation can be expected. Unlike foreign object damage (FOD) and blade failures, which in most cases creates a severe rotor 1/rev unbalance and are quickly discovered by vibration monitoring, sand and saltwater induced engine performance degradation is essentially transparent to vibration monitoring due to the uniform wear (sand erosion) and encrustation (salt water) induced circumferentially around the affected rotor. The only effective and efficient means to alert the aircrew of low engine performance conditions of this nature, outside of a protracted pilot-initiated performance check, is to capitalize on the monitoring and alarming features of the respective aircraft's HUMS. To compound these issues/concerns, mission planning to max gross weight has more often become a reality than a training exercise, and in the case of the United States Marine Corps H46 program, mission planning to power available is being explored when minimum required engine performance is a limiting factor. Thus decreasing the safety margin associated with periodic performance checks in terms of data collection frequency. For example, currently on the H46 aircraft, the aircrew is required to obtain engine performance data every 50 flight-hours, via Honeywell's Aircraft Integrated Maintenance System (AIMS), in order to assess engine performance acceptability. Acceptability is determined by whether or not the engine produces a torque (corrected by pressure altitude and outside air temperature) that is equal to or greater than minimum required, which is established by the respective engine's power turbine inlet temperature (corrected by outside air temperature). In the event that engine performance is deemed acceptable, minimum guaranteed power is used over the course of the next 50 flight-hours to aid mission planning efforts. Why is that a concern? Let's assume that performance margin (% above minimum guaranteed) was 0%. If we were to operate in an environment where severe sand erosion and salt encrustation could be expected, we will quickly drop below

minimum guaranteed power available, though the user would not be made aware of this "low power" condition until the next 50 flight-hour performance check. Coupled with mission planning to max gross weight, the safety margin quickly deteriorates. Again, when considering the rapid rate at which these engines degrade in low altitude flights over saltwater and sand, concerns heighten when also giving consideration to the frequency in which engine performance data is being collected. These concerns are even more justified when considering instantaneous failures such as foreign object damage and blade failures, if the resultant magnitude of unbalance is not sufficient enough to exceed a vibration alarm. Furthermore, there are several additional advantages to implementing engine performance monitoring and alarming, extending beyond safety. These advantages include reduced costs per flight-hour (costs induced by man-hour expenditure, fuel, etc.), inherent in performing protracted, pilot initiated performance checks; as well as facilitating a means of migrating towards on-condition maintenance in terms of engine performance. Therefore, the Marine Corps H46 community has recently funded an initiative to accurately measure engine performance real-time and capitalize on the AIMS on-board alarming feature; essentially paving the road to on-wing engine performance monitoring.

Lim, H. C., Zunino, J. III. 2008. **"Development of active systems for military utilization."** Paper presented at the NSTI Nanotechnology Conference and Trade Show. Boston, MA, USA. 1-5 June. Abstract: The US Army is transforming into a lighter yet more lethal "objective force", all while fighting wars in the Middle East. Therefore, advanced technologies and materials are being developed and integrated into current and future weapon systems. These weapon systems must be deployable, be 70% lighter and 50% smaller than current armored combat systems, while maintaining equivalent lethality and survivability. To meet these requirements Army scientists and engineers are capitalizing on new technological breakthroughs. Members of US Army ARDEC are developing active materials and sensor systems for use on various military platforms, incorporating unique properties such as self repair, selective removal, corrosion resistance, sensing, ability to modify coatings' physical properties, colorizing, and alerting logistics staff when weapon systems require more extensive repair. The ability to custom design and integrate novel technologies into functionalized systems is the driving force towards the creation and advancement of active systems. Active systems require the development and advancement of numerous technologies across various energy domains (e.g. electrical, mechanical, chemical, optical, biological, etc.). These active systems are being utilized for condition based maintenance, battlefield damage assessment, ammunition assurance & safety, and other military applications.

Mister, J. J. 2007. ***Equipment readiness in Iraq.*** Fort Leavenworth, KS : Command and General Staff College (CGSC), School of Advanced Military Studies (SAMS) http://cgsc.cdmhost.com/cdm/singleitem/collection/p4013coll3/id/1372/rec/13

Abstract: This monograph analyzes the efficiency of the Army's doctrine regarding the management and distribution of repair parts and the impact it had on equipment readiness during Operations Iraq Freedom. The monograph argues that in order for the United States Army to improve equipment readiness there must be doctrinal changes in repair parts operations to improve receipt processing time, requisition wait time, asset visibility and the referral process. After a thorough investigation the monograph shows that ineffective repair part operations negatively impacted equipment readiness during both Desert Shield and Desert Storm and Operation Iraqi Freedom.

Needham, Paul and Christopher Snyder. 2009. ***Speed and the Fog of War: Sense and Respond Logistics in Operation Iraqi Freedom-I.*** Washington, DC: Center for Technology and National Security Policy.
http://www.ndu.edu/CTNSP/docUploaded/Case%2015%20Sense%20and%20Respond.pdf
The term "fog of war" is often associated with the commander's lack of clear information on the battlefield. "War is inherently volatile, uncertain, complex, and ambiguous. For this condition, contemporary U.S. military usage offers the acronym VUCA." Compounding the "fog of war" on the modern battlefield is the high tempo of operations or speed sought by commanders to overwhelm and defeat the enemy. This case study proposes that the use of sense and respond (S&R) logistics during Operation Iraqi Freedom (OIF-I) would have provided logisticians critical decision making information (situational awareness) thereby reducing the fog of war and facilitating more efficient and responsive support to the warfighter. In drawing this conclusion, the following study analyzes the events of OIF-I, citing logistical lessons learned and difficulties experienced, and offers suggestions to reduce those challenges.
The implementation of S&R logistics will shape future joint logistics requirements while driving changes in joint doctrine and how we support the operational environment. Current efforts under the Forces Transformation and Resources Office (formerly the Office of Force Transformation) and the Program Manager, Light Armored Vehicle (PMLAV) pave a path for S & R logistics implementation within the military. Lastly, the study highlights the current Marine Corps logistics operations in Iraq and offers some insight into the future. An initial overview examines the events that led to the overthrow of Saddam Hussein.

Srinivasa, P., Zachos, M. P. 2009. **"Vehicle embedded health monitoring and diagnostic system: The mini-vehicle computer system"** Paper presented at the AUTOTESTCON, Anaheim, CA, 14-17 Sept. 2009.
Abstract: This paper will cover the background, current spiral developments, roll out, and sustainment of the US Army's newest At-Platform Automatic Test Systems (APATS) equipment for TWVs (Tactical Wheeled Vehicles). The equipment, called the SWICE (Smart Wireless Internal Combustion Engine) system, was developed for vehicle diagnostics systems in at-

platform and embedded applications, including prognostics. Based on the WICE (Wireless Internal Combustion Engine) kit, consisting of hardware devices, software applications and other interface components, the Army's Product Director-Test, Measurement & Diagnostic Equipment (PD-TMDE) supported SWICE kit provides a low cost Embedded Computer System supporting CBM (Condition Based Maintenance) system deployment. An overview of the SWICE system operation is described, including the Smart Wireless Diagnostic Sensor (SWDS) device, features of the Vehicle Integrated Diagnostics Software-Field (VIDS-F) implementation, and the vehicle Diagnostics Software (DS) application. Also covered will be the functions of the Prognostics Client "plug-in" module and integrated support for the Common Logistic Operating Environment (CLOE) implementation. Finally, the potential for coordinating new industry standards for developing common prognostic functions via IEEE, SAE, ISO, and other allied standards organizations will be presented, along with the concept of leveraging the SWICE/SWDS as a "Mini-Vehicle Control System (VCS)".

Williams, KB. 2011. **"RESET Aviation Maintenance Program Study of U.S. Army Aviation."** Masters Thesis, Western Kentucky University. http://digitalcommons.wku.edu/theses/1044
Abstract: U.S. Army helicopter maintenance condition is affected by operation environment and high flight hours. Due to the environmental conditions and high operation tempo of Afghanistan and Iraq, U.S. Army Aviation created the RESET aviation maintenance program to provide restorative maintenance following deployments in theater. The RESET maintenance program was created in addition to the existing two-level maintenance programs. Following deployment, RESET is a thorough cleaning to remove contaminants, inspection of airframe and components, and repair cycle to restore the condition of the helicopter to acceptable condition. Based on the original intent of RESET, it was projected that at the conclusion of military operations in Afghanistan and Iraq, the RESET maintenance program could be discontinued. Because of the presumed safety, reliability, and mission readiness created by RESET, this thesis appraised the RESET maintenance program as a permanent addition to U.S. Army Aviation maintenance programs.

10.3.3 Military Policies, Roadmaps

CBM+ Action Group. 2008. *Condition Based Maintenance Plus DoD Guidebook*. Washington, DC: Department of Defense. Available: http://www.acq.osd.mil/log/mpp/cbm+/CBM_DoD_Guidebook_May08.pdf

Cougaar Software. 2009. *Sense & Respond Logistics Technology Roadmap*. Washington, DC: Department of Defense. Available: http://www.cougaarsoftware.com/srl/srl-report-download.htm

Deputy Under Secretary of Defense for Logistics and Materiel Readiness. 2008. *Condition Based Maintenance Plus DoD Guidebook*. Washington, DC: Department of Defense. http://www.acq.osd.mil/_log/mrmp/CBM+.htm.

Department of Defense. 2007. *Instruction 4151.22 Condition Based Maintenance Plus (CBM+) for Materiel Maintenance.* Washington, DC: Department of Defense. Available: http://www.acq.osd.mil/log/mpp/policy/dodi_415122.pdf.

This is the official CBM+ policy of the DoD, however the *CBM+ Guidebook* provides guidance on how to apply the policy. Other maintenance policies are listed here: http://www.acq.osd.mil/log/mpp/policy.html

Department of Defense. 2012. *Defense Acquisition Guidebook (DAG)*. Washington, DC: Department of Defense. Available: http://at.dod.mil/docs/DefenseAcquisitionGuidebook.pdf
See especially Chapter 5 : *Life-Cycle Logistics.*

Department of the Navy. 2007. *Condition-Based Maintenance (CBM) Policy*. Washington, DC: Department of Defense. Available: http://www.acq.osd.mil/log/mpp/cbm+/Navy/OPNAVINST4790.16A.pdf

Smith, Timothy. 2003. *USAF Condition-Based Maintenance Plus (CBM+) Initiative* [AFLMA Report LM200301800]. Maxwell AFB, AL: Air Force Logistics Management Agency. Available: http://www.acq.osd.mil/log/mpp/cbm+/Air_Force/AFLMA%20CBM%20final%20Sep%2003.pdf
This report is a little old now, but it lays out the basic concerns and strategies of the USAF with regards to CBM+.

Woolley, Anthony. 2010. *The Sustainment Management Support Project.* Fishermans Bend, Australia: Defence Science and Technology Organisation (DSTO). Available: http://dspace.dsto.defence.gov.au/dspace/bitstream/1947/10076/1/DSTO-TN-0966%20PR.pdf

10.3.4 Standards

The following standards are related to condition based maintenance and could be important references when considering CBM implementation.

10.3.4.1 Society of Automotive Engineers (SAE)

Published Standards

AIR1828B: Guide to Engine Lubrication System Monitoring
Author(s): E-32 Aerospace Propulsion Systems Health Management - 2005-06-27

AIR1839C: A Guide to Aircraft Turbine Engine Vibration Monitoring Systems
Author(s): E-32 Aerospace Propulsion Systems Health Management - 2008-02-16

AIR1871C: Lessons Learned From Developing, Implementing, and Operating a Health Management System for Propulsion and Drive Train Systems
Author(s): E-32 Aerospace Propulsion Systems Health Management - 2011-01-03

AIR1872B: Guide to Life Usage Monitoring and Parts Management for Aircraft Gas Turbine Engines
Author(s): E-32 Aerospace Propulsion Systems Health Management – 2011-09-29

AIR1873: Guide to Limited Engine Monitoring Systems for Aircraft Gas Turbine Engines
Author(s): E-32 Aerospace Propulsion Systems Health Management - 1988-05-05

AIR1900A: Guide to Temperature Monitoring in Aircraft Gas Turbine Engines
Author(s): E-32 Aerospace Propulsion Systems Health Management - 1997-11-01

AIR4061B: Guidelines for Integrating Typical Engine Health Management Functions Within Aircraft Systems
Author(s): E-32 Aerospace Propulsion Systems Health Management - 2008-02-14

AIR4174: A Guide to Aircraft Power Train Monitoring
Author(s): E-32 Aerospace Propulsion Systems Health Management - 2002-03-06

AIR4175A: A Guide to the Development of a Ground Station for Engine Condition Monitoring
Author(s): E-32 Aerospace Propulsion Systems Health Management - 2005-02-16

AIR4176: Cost Versus Benefits of Engine Monitoring Systems
Author(s): E-32 Aerospace Propulsion Systems Health Management - 1995-10-01

AIR4830 : Aircraft Tire Condition Monitoring Systems
Author(s): A-5C Aircraft Tires Committee - 2011-04-11

AIR4985: A Methodology for Quantifying the Performance of an Engine Monitoring System
Author(s): E-32 Aerospace Propulsion Systems Health Management - 2005-01-05

AIR5120: Engine Monitoring Systems Reliability and Validity
Author(s): E-32 Aerospace Propulsion Systems Health Management - 2006-11-15

AIR5317: A Guide to Apu Health Management
Author(s): E-32 Aerospace Propulsion Systems Health Management - 2006-03-24

AIR5871: Prognostics for Gas Turbine Engines
Author(s): E-32 Aerospace Propulsion Systems Health Management - 2008-06-09

ARD50002: A Discussion of Standardization Concepts for Condition Monitoring and Performance Analysis Software

Author(s): E-32 Aerospace Propulsion Systems Health Management - 1992-11-05

ARD50069: Neural Network Applications for Engine Condition Monitoring
Author(s): E-32 Aerospace Propulsion Systems Health Management - 2002-03-22

ARP1587B: Aircraft Gas Turbine Engine Health Management System Guide
Author(s): E-32 Aerospace Propulsion Systems Health Management - 2007-05-21

ARP5783: Health and Usage Monitoring Metrics, Monitoring the Monitor
Author(s): E-32 Aerospace Propulsion Systems Health Management - 2008-02-19

AS4831A: Software Interfaces for Ground-Based Monitoring Systems
Author(s): E-32 Aerospace Propulsion Systems Health Management - 2003-02-10

AS5391: Health and Usage Monitoring System Accelerometer Interface Specification
Author(s): E-32 Aerospace Propulsion Systems Health Management -2002-12-12

AS5392: Health and Usage Monitoring System, Rotational System Indexing Sensor Specification
Author(s): E-32 Aerospace Propulsion Systems Health Management - 2002-12-12

AS5393: Health and Usage Monitoring System, Blade Tracker Interface Specification
Author(s): E-32 Aerospace Propulsion Systems Health Management 2002-12-12

AS5394: Health and Usage Monitoring System, Advanced Multipoint Interface Specification
Author(s): E-32 Aerospace Propulsion Systems Health Management - 2002-02-22

AS8054: Airborne Engine Vibration Monitoring (EVM) System, Guidelines for Performance Standard For
Author(s): E-32 Aerospace Propulsion Systems Health Management - 1996-05-01

J1655_199608: Predictive and Preventive Diagnostic Maintenance of Hydraulic Systems
Author(s): Industrial Fluid Power Components - 1996-08-01

JA1011_200908: Evaluation Criteria for Reliability-Centered Maintenance (RCM) Processes
Author(s): G-11M, Maintainability, Supportability and Logistics - 2009-08-26

JA1012_201108: A Guide to the Reliability-Centered Maintenance (Rcm) Standard
Author(s): G-11M, Maintainability, Supportability and Logistics - 2011-08-22

SAE Work in Progress Standards

AIR1900B: Guide to Temperature Monitoring in Aircraft Gas Turbine Engines
WIP- Not available for purchase at this time
Author(s): E-32 Aerospace Propulsion Systems Health Management - 2010-10-06

AIR4175B: A Guide to the Development of a Ground Station for Engine Condition Monitoring
WIP- Not available for purchase at this time
Author(s): E-32 Aerospace Propulsion Systems Health Management - 2011-04-13

AIR5773: Use of the In-System Oil Filter to Support Condition Based Maintenance
WIP- Not available for purchase at this time
Author(s): E-32 Aerospace Propulsion Systems Health Management - 2007-10-06

AIR5909: Validation and Verification of Fault Detection, Isolation and Prediction Algorithms for Engine Health Management
WIP- Not available for purchase at this time
Author(s): E-32 Aerospace Propulsion Systems Health Management - 2008-04-04

AIR6168: Landing Gear Structural Health Monitoring
WIP- Not available for purchase at this time
Author(s): A-5b Gears, Struts and Couplings Committee - 2010-11-30

ARP6204: Condition Based Maintenance (CBM) Recommened Practices
WIP- Not available for purchase at this time
Author(s): G-11r, Reliability Committee - 2011-09-15

ARP6461: Guidance on Structural Health Monitoring for Aerospace Applications
WIP- Not available for purchase at this time
Author(s): G-11shm, Structural Health Monitoring And Mgmt (Aisc) - 2011-06-06

10.3.4.2 Machinery Information Management Open Standards Alliance (MIMOSA)

OSA-EAI 3.2.2: **Open System Architecture for Enterprise Application Integration (OSA-EAI)**
This standard is at revision 3.2.2 but other revisions are also available on their website:
http://www.mimosa.org/?q=resources/specs

OSA-CBM 3.3.1: **Open System Architecture for Condition-Based Maintenance V3.3.1 Production Specification** - New Binary Specification and Web Service Interface (WSDL) included in this revision. Other revisions are also available on their website. For a brief description of the standard, see:
http://www.mimosa.org/?q=resources/specs/osa-cbm-330

10.3.4.3 Institute for Electrical and Electronics Engineers (IEEE)

1451.0-2007 : IEEE Standard for a Smart Transducer Interface for Sensors and Actuators - Common Functions, Communication Protocols, and Transducer Electronic Data Sheet (TEDS) Formats
Search for the rest of the 1451 suite of standards at: http://standards.ieee.org/

1232-2010: IEEE Standard for Artificial Intelligence Exchange and Service Tie to All Test Environments (AI-ESTATE)

1445-1998: IEEE Standard for Digital Test Interchange Format (DTIF)

1546-2000: IEEE Guide for Digital Test Interchange Format (DTIF) Application

1636-2009: IEEE Trial-Use Standard for Software Interface for Maintenance Information Collection and Analysis (SIMICA)

1636.1-2007: IEEE Trial-Use Standard for Software Interface for Maintenance Information Collection and Analysis (SIMICA): Exchanging Test Results and Session Information via the eXtensible Markup Language(XML)

1636.2-2010: IEEE Trial-Use Standard for Software Interface for Maintenance Information Collection and Analysis (SIMICA): Exchanging Maintenance Action Information via the Extensible Markup Language (XML)

1671.1-2009: IEEE Trial-Use Standard for Automatic Test Markup Language (ATML) for Exchanging Automatic Test Equipment and Test Information via XML: Exchanging Test Descriptions

1671.6-2008: IEEE Trial-Use Standard for Automatic Test Markup Language (ATML) for Exchanging Automatic Test Information via XML: Exchanging Test Station Information

10.3.4.4 International Standards Organization (ISO)

Published Standards

ISO 13372:2004
Condition monitoring and diagnostics of machines -- Vocabulary
Edition: 1 2004-05-27

ISO 13373-1:2002
Condition monitoring and diagnostics of machines -- Vibration condition monitoring -- Part 1: General procedures
Edition: 1 2002-02-28

ISO 13373-2:2005
Condition monitoring and diagnostics of machines -- Vibration condition monitoring -- Part 2: Processing, analysis and presentation of vibration data
Edition: 1 2005-07-27

ISO 13374-1:2003
Condition monitoring and diagnostics of machines -- Data processing, communication and presentation -- Part 1: General guidelines
Edition: 1 2003-03-13

ISO 13374-2:2007
Condition monitoring and diagnostics of machines -- Data processing, communication and presentation -- Part 2: Data processing
Edition: 1 2007-07-09

ISO 13379:2003
Condition monitoring and diagnostics of machines -- General guidelines on data interpretation and diagnostics techniques
Edition: 1 2003-08-19

ISO 13381-1:2004
Condition monitoring and diagnostics of machines -- Prognostics -- Part 1: General guidelines
Document available as of: 2004-11-08

ISO 13381-1:2004
Condition monitoring and diagnostics of machines -- Prognostics -- Part 1: General guidelines
Edition: 1 2004-11-08

ISO 14963:2003
Mechanical vibration and shock -- Guidelines for dynamic tests and investigations on bridges and viaducts
Edition: 1 2003-12-01

ISO 16587:2004
Mechanical vibration and shock -- Performance parameters for condition monitoring of structures
Edition: 1 2004-09-22

ISO 16587:2004
Mechanical vibration and shock -- Performance parameters for condition monitoring of structures
Edition: 1 2004-09-22

ISO 17359:2011
Condition monitoring and diagnostics of machines -- General guidelines
Edition: 2 2011-04-07

ISO 18434-1:2008
Condition monitoring and diagnostics of machines -- Thermography -- Part 1: General procedures
Edition: 1 2008-02-22

ISO 18435-1:2009
Industrial automation systems and integration -- Diagnostics, capability assessment and maintenance applications integration -- Part 1: Overview and general requirements
Edition: 1 2009-08-13

ISO 18436-1:2004
Condition monitoring and diagnostics of machines -- Requirements for training and certification of personnel -- Part 1: Requirements for certifying bodies and the certification process
Edition: 1 2004-10-01

ISO 18436-2:2003
Condition monitoring and diagnostics of machines -- Requirements for training and certification of personnel -- Part 2: Vibration condition monitoring and diagnostics
Edition: 1 2003-11-07

ISO 18436-3:2008
Condition monitoring and diagnostics of machines -- Requirements for qualification and assessment of personnel -- Part 3: Requirements for training bodies and the training process
Edition: 1 2008-02-11

ISO 18436-4:2008
Condition monitoring and diagnostics of machines -- Requirements for qualification and assessment of personnel -- Part 4: Field lubricant analysis
Edition: 1 2008-10-20

ISO 18436-6:2008
Condition monitoring and diagnostics of machines -- Requirements for qualification and assessment of personnel -- Part 6: Acoustic emission
Edition: 1 2008-10-20

ISO 18436-7:2008
Condition monitoring and diagnostics of machines -- Requirements for qualification and assessment of personnel -- Part 7: Thermography
Edition: 1 2008-10-20

ISO 2041:2009
Mechanical vibration, shock and condition monitoring -- Vocabulary
Edition: 3 2009-07-17

ISO 22096:2007
Condition monitoring and diagnostics of machines -- Acoustic emission
Edition: 1 2007-07-10

ISO 29821-1:2011
Condition monitoring and diagnostics of machines -- Ultrasound -- Part 1: General guidelines
Edition: 1 2011-04-15

ISO/IEC 24791-1:2010
Information technology -- Radio frequency identification (RFID) for item management -- Software system infrastructure -- Part 1: Architecture
Edition: 1 2010-08-06

ISO/IEC 24791-2:2011
Information technology -- Radio frequency identification (RFID) for item management -- Software system infrastructure -- Part 2: Data management
Edition: 1 2011-10-14

ISO Standards Under Development

ISO/CD 20958-1
Condition monitoring and diagnostics of machines -- Electrical signature analysis -- Part 1: Three-phase induction motors
Edition: 1 2011-11-15

ISO/FDIS 13379-1
Condition monitoring and diagnostics of machines -- Data interpretation and diagnostics techniques -- Part 1: General guidelines
Edition: 1 2011-09-26

ISO/DIS 18436-5
Condition monitoring and diagnostics of machines -- Requirements for qualification and assessment of personnel -- Part 5: Lubricant laboratory technician/analyst
Edition: 1 2009-06-19

ISO/DIS 13372
Condition monitoring and diagnostics of machines -- Vocabulary
Edition: 2 2011-05-17

ISO/DIS 18436-1
Condition monitoring and diagnostics of machines -- Requirements for qualification and assessment of personnel -- Part 1: Requirements for assessment bodies and the assessment process
Edition: 2 2011-06-07

ISO/DIS 18436-2
Condition monitoring and diagnostics of machines -- Requirements for qualification and assessment of personnel -- Part 2: Vibration condition monitoring
Edition: 2 2011-06-15

ISO/CD 18436-8
Condition monitoring and diagnostics of machines -- Requirements for qualification and assessment of personnel -- Part 8: Ultrasound
Edition: 1 2011-02-01

ISO/FDIS 13374-3
Condition monitoring and diagnostics of machines -- Data processing, communication and presentation -- Part 3: Communication
Edition: 1 2011-11-30

10.3.4.5 NATO Standards

AECTP-600 (Edition 2, 2007)
The Ten Step Method for Evaluating the Ability of Materiel to meet Extended Life Requirements and Role and Deployment Changes

ALP-10 (Edition 2, 2011)

NATO Guidance on Integrated Logistics Support for Multinational Armament Programmes

AUIDP-1
NATO Guidance on Unique Identification (UID) of Items

NATO STANAG 2233
NATO Consignment and Asset Tracking by Radio Frequency Identification

NATO STANAG 2290
NATO Unique Identification of Items

NATO STANAG 2495
Data Formats for Asset Tracking

NATO ARMP-1
NATO Requirements for Reliability and Maintainability.

NATO ARMP-4
Guidance for Writing NATO R&M Requirements Documents

NATO ARMP-6
Guidance for Managing In-Service R&M

10.4 Glossary

Acronym	Definition
AIT	Automatic Identification Technology
AL	Autonomic Logistics
ALGS	Autonomic Logistics Global Sustainment
ALIS	Autonomic Logistics Information System
AMCOM	U.S. Army Aviation Command
ANS	Autonomic Nervous System
BIT	Built-in Test
CBA	Cost-Benefits Analysis
CBM	Condition Based Maintenance
CBM+	Condition Based Maintenance Plus
CF	Canadian Forces
CLS	Contractor Logistics Support
CONOPS	Concept of Operations
COP	Common Operating Picture
COTS	Commercial-off-the-Shelf
DIS	Distributed Information System
DND	Department of National Defense, Canada
DoD	U.S. Department of Defense
DPHM	Diagnostics, Prognostics and Health Management
DRDC	Defence Reseach & Development Canada
FEM	Finite Element Methods
FH	Flight Hour
FMC	Fully Mission Capable
GOTS	Government-off-the-Shelf
HEMTT	Heavy Expanded Mobility Tactical Trucks
HUMS	Health and Usage Monitoring Systems
ICAS	Integrated Condition Assessment System
IHM	Integrated Health Management
IPC	International Patent Classification
IUID	Item Unique Identifier
IVHM	Integrated Vehicle Health Management
JCS	Joint Chiefs of Staff
JSF	Joint Strike Fighter
KM	Knowledge Management
MA	Materiel Availability

Acronym	Definition
MDT	Mean Down Time
MEMS	Micro Electro-Mechanical Systems
MFHBME	Mean Flight Hours Between Maintenance Events
MFHBMR	Mean Flight Hours Between Maintenance Removals
MIMOSA	Machinery Information Management Open Standards Alliance
MLDT	Mean Logistics Down Time
MMH	Maintenance Man Hours
MR	Materiel Reliability
MTF	Maintenance Test Flights
MTTF	Mean Time to Failure
MTTR	Mean Time To Repair
NMCM	Non-Mission Capable for Maintenance
NRC-CISTI	National Research Council - Canada Institute for Scientific and Technical Information
O&S	Operations & Support
OC	Ownership Cost
OEM	Original Equipment Manufacturer
OR	Operational Readiness
PBL	Performance Based Logistics
PdM	Predictive Maintenance
PHM	Prognostics and Health Management
PM	Program Manager
PMC	Partially Mission Capable
PMS	Predictive Maintenance Systems
PoF	Physics of Failure
RCM	Reliability Centered Maintenance
RFID	Radio Frequency Identification
ROI	Return on Investment
RUL	Remaining Useful Life
S&RL	Sense & Respond Logistics
SBCT	Stryker Brigade Combat Team
SHM	Structural Health Monitoring
STI	Strategic Technical Insights
SWE	Sensor Web Enablement
TAV	Total Asset Visibility
TLCSM	Total Life Cycle System Management
VMI	Vendor Managed Inventory

10.5 Major Players Data

Table 5. Major Players - International

Organization Name	Co-Authoring Organizations	Top Authors	Top Subject Groups	Top Keywords	Publication Years
Harbin Institute of Technology, China[77] [43]	Dalian University of Technology, Dalian, China [13] [44] Missouri University of Science and Technology, Rolla, MO, United States [2]; Polish Academy of Sciences, Gdansk, Poland [2]; Acellent Technologies, Inc., Sunnyvale, CA, United States [1]	Ou, J. P. [21] [45] Zhong, Shisheng [16]; Li Hongru [12]; Ding, Gang [9]; Wang, Y. [6]	Structures [44]; Condition monitoring [39]; SHM [36]; Sensors [28]; Engines [21]; Civil structures / Bridges [20]; Aircraft (excl. Rotorcraft) [17]; Strain [14]; Artificial intelligence [13]; Accidents / safety [12]; Fiber optics [12]	Condition monitoring (CM) [35]; Structural health monitoring (SHM) [35]; Monitoring and control [19]; Structural engineering [14]; Sensors [13]; bridges (structures) [11]; Health monitoring [11]; Fiber Bragg Grating (FBG) [9]; Fiber optic sensors [9]; Aircraft engine condition monitoring [8]; Aircraft engines [8]; Fiber optics [8]	2006 - 2011

[43] The numbers in brackets show how many records are associated with that data element. For example, Harbin Institute has 77 records in our dataset.
[44] The numbers in brackets in each subsequent column reflect how many of the records are associated with the Organization in the first column. For example, of the 77 records for Harbin Institute of Technology, 13 of them are co-authored with Dalian University of Technology.
[45] The number in square brackets mean that, for example, of the 77 records for Harbin Institute, 21 of them are authored by Ou, J.P.

Organization Name	Co-Authoring Organizations	Top Authors	Top Subject Groups	Top Keywords	Publication Years
Impact Technologies, Rochester, NY, United States[56]	Georgia Institute of Technology, Atlanta, GA, United States [2]; Honeywell Corp., Phoenix, AZ, USA [1]; U.S. Air Force Research Laboratory (AFRL), Wright-Patterson AFB, OH, United States [1]; U.S. Army, Aviation Applied Technology Directorate, Ft. Eustis, VA United States [1]	Roemer, M. J. [22]; Byington, C. S. [13]; Kalgren, P. W. [13]; Liang Tang [11]; Vachtsevanos, G. J. [10]	PHM [33]; Diagnostics [23]; Aircraft (excl. Rotorcraft) [22]; Condition monitoring [16]; Engines [16]; Failure [14]; Modeling [14]; Health and usage monitoring [13]; Algorithms [12]; Fault diagnosis [11];	Condition monitoring (CM) [16]; Prognostics and Health Management (PHM) [16]; fault diagnosis [11]; prognostics [11]; Health management system (HMS) [10]; Condition based maintenance (CBM) [9]; Remaining Useful Life (RUL) [9]; Aircraft [8]; Aircraft maintenance [8]; Health monitoring [8]	2006 - 2011
U.S. Air Force Research Laboratory (AFRL), Wright-Patterson AFB, OH, United States[52]	University of Dayton, OH, United States [5]; Wright State University, Dayton, OH, USA [3]; McAulay Brown, Beavercreek, OH, USA [2];	Blackshire, J. [8]; Derriso, M. M. [8]; Cooney, A. [6]; Knopp, J. S. [6]; Jata, K. V. [5]; Lindgren, E. A. [5]; Olson, S. E. [5]	Aircraft (excl. Rotorcraft) [27]; Structures [24]; SHM [22]; Sensors [12]; Engines [11]; Condition monitoring [9]; Inspection & nondestructive evaluation [9]; Materials [9]; Cracks [8]; Damage detection [8];	Structural health monitoring (SHM) [21]; Aeronautics and Aerodynamics--Aircraft [11]; Aircraft [11]; Condition monitoring (CM) [9]; Aircraft maintenance [6]; Structural mechanics [6]; Cracks [5]; Damage detection [5]; Health management system (HMS) [5]; Monitoring and control [5]; Sensors [5]	2006 - 2010

Organization Name	Co-Authoring Organizations	Top Authors	Top Subject Groups	Top Keywords	Publication Years
Nanjing University of Aeronautics and Astronautics (NUAA), China[47]	Air China Technics, Beijing, China [1]; Beihang University, Beijing, China [1]; Huaiyin Normal University, Huaian, China [1]; Jinangsu Teachers University of Technology, Changzhou, China [1]	Yuan, Shenfang [15]; Qiu, L. [12]; Zuo, Hong fu [9]; Yuan, Shen fang [7]; Hongfu, Z. [5]	Aircraft (excl. Rotorcraft) [30]; Condition monitoring [19]; SHM [18]; Structures [18]; Engines [14]; Sensors [12]; Materials [10]; Costs / ROI [9]; Piezoelectric devices [9]; Modeling [8]	Condition monitoring (CM) [18]; Structural health monitoring (SHM) [18]; Aircraft [11]; Aircraft maintenance [10]; Multi-agent systems [7]; Structures (built objects) [7]; Aeroengines [6]; Aerospace components [6]; Maintenance cost [6]; Monitoring and control [6]; piezoelectric sensors [6]; Reliability [6]	2006 - 2011
University of Maryland, College Park, MD, USA[44]	City University of Hong Kong, Kowloon, Hong Kong [7]; Beihang University, Beijing, China [2]; Techno-Sciences, Inc., Beltsville, MD, USA [2]; Bell Helicopter Textron Inc., Fort Worth, TX, United States [1]	Pecht, M. [26]; Gu, J. [7]; Sandborn, P. A. [6]; Baz, A. [4]; Das, D. [4]	PHM [30]; Failure [18]; Reliability [16]; Electronics [11]; Condition monitoring [10]; Life cycle [10]; Structures [9]; Aircraft (excl. Rotorcraft) [8]; Costs / ROI [8]; Fatigue [7]; Prediction (general) [7]	Prognostics and Health Management (PHM) [19]; Health management system (HMS) [13]; Condition monitoring (CM) [10]; Failure analysis [9]; Reliability [8]; Electronic product [7]; prognostics [7]; Life cycle cost (LCC) [6]; Structural health monitoring (SHM) [6]; Fatigue [5]; Reliability prediction [5]	2006 - 2011

Organization Name	Co-Authoring Organizations	Top Authors	Top Subject Groups	Top Keywords	Publication Years
Beihang University, Beijing, China[43]	University of Maryland, College Park, MD, USA [2]; Beijing University of Aeronautics and Astronautics (BUAA), Beijing, China [1]; City University of Hong Kong, Kowloon, Hong Kong [1]; First Aeronautical Engineering Institute of Chinese Air Force, Xinyang, China [1]	Kang, R. [8]; Gao ZhanBao [4]; Li, X. [4]; Pecht, M. [4]; Chuan, Lv [3]; Gong Q. [3]; Huiguo Zhang [3]; Ma, Lin [3]; Xingshan, L. [3]; Yu, Jinsong [3]; Yuan, Haiwen [3]; Zhang, H. [3]; Zhang, J. [3]; Zhao Y. [3]; Zhao, T. [3]	PHM [21]; Aircraft (excl. Rotorcraft) [16]; Engines [12]; Failure [12]; Condition monitoring [11]; Diagnostics [11]; Fault diagnosis [11]; Reliability [11]; Costs / ROI [9]; Modeling [9]	Prognostics and Health Management (PHM) [16]; Condition monitoring (CM) [11]; fault diagnosis [11]; Health management system (HMS) [9]; Aircraft [8]; Engine maintenance [7]; Condition based maintenance (CBM) [6]; Maintenance [6]; Reliability [6]; Aircraft maintenance [5]; Failure analysis [5]; Fault detection [5]; Maintainability [5]	2007 - 2011

Organization Name	Co-Authoring Organizations	Top Authors	Top Subject Groups	Top Keywords	Publication Years
NASA Ames Research Center, Moffett Field, CA, United States[43]	Arizona State University, Tempe, AZ, USA [3]; GE Global Research, Niskayuna, NY, USA [2]; NASA Glenn Research Center, Cleveland, OH, USA [2]; ADAPT, Discovery and Systems Health, MS [1]	Goebel, K. F. [11]; Saha, S. [8]; Celaya, J.R. [7]; Schwabacher, M. A. [7]; Saha, B. [5]; Saxena, A. [5]; Wysocki, P. [5]	Engines [13]; Failure [13]; Space applications [11]; Diagnostics [10]; PHM [10]; Aircraft (excl. Rotorcraft) [9]; Electronics [9]; Sensors [8]; Structures [8]; Condition monitoring [7]; Fault detection [7]; Health and usage monitoring [7]	Condition monitoring (CM) [7]; Health management system (HMS) [7]; fault diagnosis [6]; Launch vehicle [6]; Structural health monitoring (SHM) [6]; Fault detection [5]; Health monitoring system [5]; Algorithms [4]; Avionics [4]; Cracks [4]; Engine maintenance [4]; Failure [4]; Integrated System Health Management (ISHM) [4]; prognostics [4]; Prognostics and Health Management (PHM) [4]; remaining life assessment [4]; Remaining Useful Life (RUL) [4]	2006 - 2011

Organization Name	Co-Authoring Organizations	Top Authors	Top Subject Groups	Top Keywords	Publication Years
Pennsylvania State University, University Park, PA, USA[41]	Bell Helicopter Textron Inc., Fort Worth, TX, United States [2]; FBS, Inc., State College, PA, United States [2]; BAE Systems, United States [1]	Rose, J. L. [10]; Reichard, K. [8]; Banks, J. [7]; Gao, H. [4]; Ray, A. [4]	Condition monitoring [20]; Aircraft (excl. Rotorcraft) [16]; Structures [15]; SHM [14]; Diagnostics [10]; Sensors [10]; Ultrasonics [10]; CBM [8]; Engines [8]; Inspection & nondestructive evaluation [7];	Condition monitoring (CM) [20]; Structural health monitoring (SHM) [14]; Condition based maintenance (CBM) [8]; Sensors [7]; Aircraft [6]; Engine maintenance [6]; Structural engineering [6]; Costs [5]; Maintenance [5]; Military vehicles [5]	2006 - 2011
Georgia Institute of Technology, Atlanta, GA, United States[40]	Impact Technologies, Rochester, NY, United States [2]; Hong Kong Polytechnic University, Kowloon, Hong Kong [1]; Intelligent Automation, Inc., Rockville, MD, United States [1]	Vachtsevanos, G. J. [9]; Michaels, J. E. [6]; Habetler T. G. [5]; Michaels, T. E. [5]; Zhang, B. [5]	Condition monitoring [16]; SHM [14]; Structures [14]; Diagnostics [13]; Aircraft (excl. Rotorcraft) [12]; Sensors [12]; Fault diagnosis [11]; Engines [10]; Failure [9]; PHM [9]	Condition monitoring (CM) [16]; Structural health monitoring (SHM) [13]; fault diagnosis [10]; Condition based maintenance (CBM) [8]; Aerospace components [6]; Remaining Useful Life (RUL) [6]; Sensors [6]; Structural engineering [6]; Aircraft [5]; Helicopters [5]; Operating condition [5]; particle filtering (numerical methods) [5]; vibration [5]	2006 - 2011

Organization Name	Co-Authoring Organizations	Top Authors	Top Subject Groups	Top Keywords	Publication Years
University of California, San Diego, CA, United States[38]	Los Alamos National Laboratory, Los Alamos, NM, USA [6]; Drexel University, Philadelphia, PA, United States [2]; State University of New York (SUNY), Buffalo, NY, United States [2]; Universita degli Studi di Palermo, Italy [2]	Lanza Di Scalea, F. [13]; Bartoli, I. [11]; Farrar, C. R. [10]; Todd, M. D. [9]; Salamone, S. [8]	SHM [30]; Structures [27]; Aircraft (excl. Rotorcraft) [17]; Sensors [16]; Condition monitoring [15]; Ultrasonics [13]; Materials [12]; Damage detection [10]; Modeling [10]; Finite element methods (FEM) [9]; Piezoelectric devices [9]	Structural health monitoring (SHM) [29]; Condition monitoring (CM) [15]; Sensors [10]; Structural engineering [9]; Damage detection [8]; Guided electromagnetic wave propagation [8]; Aerospace components [7]; Finite element analysis [7]; Health monitoring [7]; Remotely operated vehicles [7]; Ultrasonics [7]; Unmanned aerial vehicles (UAV) [7]	2006 - 2011

Organization Name	Co-Authoring Organizations	Top Authors	Top Subject Groups	Top Keywords	Publication Years
NASA Glenn Research Center, Cleveland, OH, USA[36]	U.S. Army Research Laboratory (ARL), Cleveland, OH, United States [3]; U.S. Army, Redstone Arsenal, AL, United States [3]; NASA Ames Research Center, Moffett Field, CA, United States [2]; Alliant Techsystems, Inc., Hampton, VA, United States [1]	Dempsey, P. J. [9]; Simon, D. L. [7]; Abdul-Aziz, A. [5]; Woike, M. R. [5]; Baaklini, G. Y. [4]; Briggs, J. L. [4]; Lekki, J. D. [4]; Reveley, M. S. [4]; Wade, D. R. [4]	Aircraft (excl. Rotorcraft) [21]; Engines [16]; Rotorcraft [13]; Accidents / safety [11]; Health and usage monitoring [11]; Propulsion systems [9]; Cracks [8]; Failure [8]; Structures [8]; Diagnostics [7]; Fault detection [7]	Aeronautics and Aerodynamics--Aircraft [8]; Aircraft engines [7]; Structural health monitoring (SHM) [7]; Condition monitoring (CM) [5]; Fault detection [5]; Health monitoring [5]; Helicopters [5]; Maintenance [5]; Turbines [5]; Aircraft [4]; Condition based maintenance (CBM) [4]; Condition indicators [4]; Disks (structural components) [4]; Flight safety [4]; Health monitoring system [4]; NASA [4]; Nondestructive testing (NDT) [4]; Rotors [4]; Sensors [4]	2006 - 2011

Organization Name	Co-Authoring Organizations	Top Authors	Top Subject Groups	Top Keywords	Publication Years
Northwestern Polytechnical University, Xi'an, China[36]		Wan, F. [7]; Song, BiFeng [6]; Wang, Z. [3]; Feng, YunWen [2]; Guo, Yang ming [2]; Mingming Sun [2]; Shen, T. [2]; Wang, H. [2]; Wang, Haifeng [2]; Wang, Z. S. [2]; Wu, Y. [2]; Xuan JianLin [2]; Yu, Z. [2]; Zhai, Zhengjun [2]; Zhang, Bao zhen [2]; Zimin Yang [2]	Aircraft (excl. Rotorcraft) [23]; Condition monitoring [18]; Accidents / safety [14]; Diagnostics [13]; Fault diagnosis [12]; Structures [12]; Sensors [10]; Failure [9]; SHM [8]; Simulation [8]	Condition monitoring (CM) [18]; Aircraft [12]; fault diagnosis [12]; Health management system (HMS) [7]; Health monitoring [7]; Prognostics and Health Management (PHM) [7]; Structural health monitoring (SHM) [7]; Aircraft maintenance [6]; Failure analysis [6]; Fault detection [5]; Finite element analysis [5]; Space vehicles [5]	2006 - 2011

Organization Name	Co-Authoring Organizations	Top Authors	Top Subject Groups	Top Keywords	Publication Years
University of Michigan, Ann Arbor, MI, United States[34]	Scripps Institute of Oceanography, San Diego, CA, United States [1]; Shimizu Corporation, Tokyo, Japan [1]; U.S. Air Force Research Laboratory (AFRL), Kirtland AFB, NM, United States [1]; University of California, Davis, CA, United States [1]	Lynch, J. P. [12]; Ni, J. [4]; Cesnik, C.E.S. [3]; Hou, T.-C. [3]; Junhee Kim [3]; Li, L. [3]; Najafi K [3]; Zimmerman, A. T. [3]	Structures [17]; SHM [14]; Sensors [13]; Condition monitoring [12]; Wireless systems [12]; Sensor networks [10]; Civil structures / Bridges [9]; CBM [6]; Materials [6]; Modeling [6];	Structural health monitoring (SHM) [12]; Condition monitoring (CM) [11]; Wireless sensor networks (WSN) [10]; bridges (structures) [6]; Condition based maintenance (CBM) [6]; Sensors [6]; Structural engineering [6]; Monitoring and control [4]; vibration [4]; Automation [3]; Damage detection [3]; Decision making [3]; energy harvesting [3]; Guided wave propagation [3]; Maintainability [3]; Maintenance policy [3]; Space vehicles [3]; Wireless sensors [3]	2006 - 2011

Organization Name	Co-Authoring Organizations	Top Authors	Top Subject Groups	Top Keywords	Publication Years
University of Sheffield, United Kingdom[34]	University of Sheffield, United Kingdom [34]; Cardiff University, Cardiff, Wales, United Kingdom [2]; Los Alamos National Laboratory, Los Alamos, NM, USA [2]; University of Central Lancashire, Preston, United Kingdom [2]; European Aeronautic Defence and Space Company (EADS), Munich, Germany [1]	Worden, K. [18]; Manson, G. [11]; Boller, C. [7]; Barthorpe, R. J. [6]; Staszewski, W. J. [5]	SHM [28]; Aircraft (excl. Rotorcraft) [26]; Structures [26]; Condition monitoring [17]; Damage detection [15]; Materials [11]; Fatigue [9]; Inspection & nondestructive evaluation [8]; Ultrasonics [8]; Artificial intelligence [6]; Manufacturing / production [6]	Structural health monitoring (SHM) [28]; Aircraft [17]; Condition monitoring (CM) [17]; Damage detection [13]; Structures (built objects) [11]; Aerospace components [7]; Aircraft manufacture [6]; Aircraft wing [6]; Airframes [6]; Structural engineering [6]	2006 - 2011
Beijing University of Aeronautics and Astronautics (BUAA), Beijing, China[31]	Beijing University of Aeronautics and Astronautics (BUAA), Beijing, China [31]; Beihang University, Beijing, China [1]; Naval Aeronautical Engineering Institute, Yantai, China [1]; Shaanxi Normal University, Xi'an, China [1]; Shenyang Aircraft Design Institute, Shenyang, China [1]	Kang, R. [5]; Zhang, L. [4]; Zhao, T. [3]; Han L. [2]; Hong J. [2]; Hong, L. [2]; Li, X. [2]; Ma Qishuang [2]; Sun, B. [2]; Wang, Shaoping [2]; Wang, Xiaoyun [2]; Xie Jin song [2]; Yu, Jinsong [2]; Yuan, Haiwen [2]; Zhang Ping [2]; Zhang, S. [2]	PHM [16]; Aircraft (excl. Rotorcraft) [14]; Condition monitoring [14]; Diagnostics [12]; Engines [11]; Fault diagnosis [9]; Reliability [9]; CBM [6]; Failure [5]; Modeling [5];	Condition monitoring (CM) [14]; fault diagnosis [9]; Health management system (HMS) [9]; Engine maintenance [8]; Prognostics and Health Management (PHM) [8]; Aircraft [7]; Condition based maintenance (CBM) [6]; prognostics [6]; Reliability [5]; decision support systems (DSS) [4]; Failure analysis [4]; Fault prognostics [4]	2006 - 2011

Organization Name	Co-Authoring Organizations	Top Authors	Top Subject Groups	Top Keywords	Publication Years
University of Tokyo, Japan[31]	RIMCOF, Tokyo, Japan [6]; Mitsubishi Electric Corp., Japan [5]; University of Illinois at Urbana-Champaign, Urbana, IL, United States [4]; Fuji Heavy Industries Ltd., Tochigi, Japan [2]; Texas Tech University, Lubbock, TX, United States [2]	Takeda, N. [18]; Okabe, Y. [5]; Hotate, K. [4]; Minakuchi, S. [4]; Nagayama, T. [4]; Ozaki, T. [4]; Spencer Jr., B. F. [4]	Structures [28]; Sensors [26]; SHM [24]; Aircraft (excl. Rotorcraft) [17]; FBG sensors [14]; Fiber optics [14]; Materials [12]; Strain [12]; Damage detection [11]; Condition monitoring [10]; Civil structures / Bridges [6]	Structural health monitoring (SHM) [24]; Fiber Bragg Grating (FBG) [12]; Fiber optic sensors [11]; Sensors [11]; Aircraft [10]; Condition monitoring (CM) [10]; Damage detection [10]; Composite materials [9]; FBG sensors [9]; Fiber optics [8]	2006 - 2011
Shanghai Jiaotong University, Shanghai, China[30]	U.S. Army, Redstone Arsenal, AL, United States [1]; University of Illinois at Chicago, IL, USA [1]	Dong Ming [8]; Meng G. [4]; Peng, Y. [4]; Chen, J. [3]; Ming Yi You [3]; Xi L. [3]	CBM [26]; Condition monitoring [16]; Engines [14]; Diagnostics [11]; Decision support [9]; Modeling [9]; Prediction (general) [9]; Algorithms [8]; Fault diagnosis [8]; PHM [8]	Condition based maintenance (CBM) [25]; Condition monitoring (CM) [16]; Engine maintenance [14]; Decision making [8]; fault diagnosis [7]; Hidden Markov models [6]; Reliability [5]; Hydraulic pump [4]; machine bearings [4]; Pumps [4]	2006 - 2011

Organization Name	Co-Authoring Organizations	Top Authors	Top Subject Groups	Top Keywords	Publication Years
NASA Langley Research Center, Hampton, VA, United States[28]	Alliant Techsystems, Inc., Hampton, VA, United States [1]; Arizona State University, Tempe, AZ, USA [1]; Dongguk University-Seoul, South Korea [1]	Winfree, W. P. [4]; Wu, M. C. [4]; Allison, S. G. [2]; Atkinson GM [2]; Cox, D. E. [2]; Cunningham, K. [2]; Mielnik, J. J. [2]; Morelli E. A. [2]; Murch, A. M. [2]; Ross, R. W. [2]; Wilson WC [2]	Aircraft (excl. Rotorcraft) [12]; Sensors [12]; Accidents / safety [9]; SHM [9]; Structures [8]; Electronics [7]; Health and usage monitoring [7]; Materials [6]; Failure [5]; IVHM [5]; IVHM [5]; Modeling [5]	Structural health monitoring (SHM) [9]; Health monitoring system [6]; Avionics [5]; integrated vehicle health management (IVHM) [5]; Aerospace vehicles [4]; Bragg gratings [4]; Composite materials [4]; Delamination [4]; Fiber optics [4]; Temperature sensors [4]; Thermography [4]	2006 - 2011
University of South Carolina, Columbia, SC, USA[28]	Republic of Korea Army, Seoul, South Korea [1]; U.S. Air Force Office of Scientific Research, Arlington, VA, USA [1]; U.S. Army Materiel Systems Analysis Activity (AMSAA), Aberdeen Proving Ground, MD, USA [1]; University of Texas at Arlington, TX, United States [1]	Giurgiutiu, V. [15]; Bayoumi, A.-M. E. [9]; Goodman, N. [9]; Lingyu Yu [8]; Shah, R. [5]; Yong, June Shin [5]; Ziehl, P.H. [5]	SHM [18]; Condition monitoring [15]; Piezoelectric devices [15]; Sensors [15]; Structures [14]; Ultrasonics [11]; Aircraft (excl. Rotorcraft) [9]; Civil structures / Bridges [7]; Cracks [7]; Inspection & nondestructive evaluation [7]	Structural health monitoring (SHM) [18]; Condition monitoring (CM) [15]; Maintenance [7]; Piezoelectric wafer active sensors [7]; Acoustic emissions (AE) [6]; Lamb waves [6]; Nondestructive testing (NDT) [6]; Aircraft [5]; bridges (structures) [5]; Piezoelectric (PZT) [5]; Piezoelectric devices [5]; Structural engineering [5]	2006 - 2011

Organization Name	Co-Authoring Organizations	Top Authors	Top Subject Groups	Top Keywords	Publication Years
Dalian University of Technology, Dalian, China[27]	Harbin Institute of Technology, China [13]; Missouri University of Science and Technology, Rolla, MO, United States [2]; Tongji University, Shanghai, China [2]; Dalian University, Dalian, China [1]	Ou, J. P. [16]; Li Hongru [6]; Yu, Y. [5]; Li, Hong Nan [4]; Zhao, X. [4]	Structures [21]; SHM [18]; Sensors [14]; Civil structures / Bridges [13]; Strain [8]; Condition monitoring [7]; FBG sensors [7]; Fiber optics [7]; Damage detection [5]; Health and usage monitoring [5]	Structural health monitoring (SHM) [18]; Monitoring and control [10]; bridges (structures) [7]; Condition monitoring (CM) [7]; Fiber Bragg Grating (FBG) [6]; Fiber optic sensors [6]; Damage detection [5]; Sensors [5]; Structural engineering [5]; Offshore structures [4]; PVDF [4]	2006 - 2011

Table 6. Major Players – Canadian

Organization Name	Co-authoring Organizations	Top Authors	Top Keywords	Top Subject Groups	Publication Years
University of Toronto, ON, Canada[21]		Jardine, A. K. S. [10]; Makis V. [9]; Banjevic, D. [8]; Lin, D. [3]; Jiang, R. [2]; Jianmou Wu [2]; Montgomery, N. [2]; Wong, E. L. [2]; Yin Z. [2]; Zuashkiani A [2]	Condition based maintenance (CBM) [15]; Condition monitoring (CM) [10]; Engine maintenance [8]; Optimization [5]; Bayesian methods [4]; Proportional hazard model [4]; Control charts [3]; Covariates [3]; Decision making [3]; Hazards [3]; Maintenance cost [3]; Potential benefits [3]; vibration [3]	CBM [19]; Condition monitoring [11]; Failure [9]; Engines [8]; Decision support [6]; Modeling [5]; Costs / ROI [4]; Maintenance policies [4]; Oil / lubrication [4]; Vibration [4]	2006 - 2011
Defence R&D Canada (DRDC), Ottawa, ON, Canada[16]	National Research Council Canada, Ottawa, ON, Canada [6]; National Research Council Canada, Boucherville, QC, Canada [5]; McGill University, Montreal, QC, Canada [3]; Department of National Defence (DND), Ottawa, ON, Canada [2]; University of Ottawa, ON, Canada [2]	Mrad, Nezih [16]; Jen, C.-K. [5]; Kobayashi, M. [5]; Xiao, G. Z. [4]; Wu, K.-T. [3]	Condition monitoring (CM) [8]; Structural health monitoring (SHM) [8]; Ultrasonic transducers [6]; Aircraft [5]; Structural engineering [5]; Aerospace components [4]; Aircraft maintenance [4]; Damage detection [4]; Nondestructive testing (NDT) [4]; Sensors [4]; Sol-gel spray technique [4]	Aircraft (excl. Rotorcraft) [12]; Sensors [10]; Structures [10]; SHM [9]; Condition monitoring [8]; FBG sensors [6]; Fiber optics [6]; Ultrasonics [6]; Inspection & nondestructive evaluation [5]; Materials [5];	2006 - 2011

Organization Name	Co-authoring Organizations	Top Authors	Top Keywords	Top Subject Groups	Publication Years
National Research Council Canada, Ottawa, ON, Canada[14]	Defence R&D Canada (DRDC), Ottawa, ON, Canada [6]; University of Ottawa, ON, Canada [3]	Mrad, Nezih [6]; Letourneau S. [4]; Martinez, M. [3]; Xiao, G. Z. [3]; Yang, Chunsheng [3]	Aircraft [6]; Condition monitoring (CM) [4]; Structural health monitoring (SHM) [4]; Aerospace components [3]; Fiber Bragg Grating (FBG) [3]; Prognostic model [3]; Prognostics and Health Management (PHM) [3]; Sensors [3]; Costs [2]; Damage detection [2]; Data mining [2]; Decision making [2]; Evaluation models [2]; Fatigue loadings [2]; Fatigue testing [2]; Fiber optics [2]; Gas turbines [2]; Health management system (HMS) [2]; Nondestructive testing (NDT) [2]; Stress concentration [2]	Aircraft (excl. Rotorcraft) [8]; Sensors [5]; Algorithms [4]; Condition monitoring [4]; Inspection & nondestructive evaluation [4]; PHM [4]; SHM [4]; Engines [3]; Fatigue [3]; FBG sensors [3]; Fiber optics [3]; Modeling [3]	2006 - 2011

Organization Name	Co-authoring Organizations	Top Authors	Top Keywords	Top Subject Groups	Publication Years
Concordia University, Montreal, QC, Canada[12]		Tian, Zhigang [7]; Barua, A. [4]; Khorasani, K. [4]; Jin, T. [3]; Zuo MJ [2]	Condition monitoring (CM) [10]; Condition based maintenance (CBM) [6]; Engine maintenance [5]; Artificial neural network (ANNs) [3]; Maintenance cost [3]; Monitoring and control systems [3]; Multiple components [3]; Neural networks [3]; Satellites formation [3]; Simulation [3]; Telemetry data [3]; Turbine components [3]; Wind power generation systems [3]; Wind turbines [3]	Condition monitoring [10]; Artificial intelligence [7]; CBM [6]; Engines [6]; Costs / ROI [5]; Failure [4]; Decision support [3]; Diagnostics [3]; Fault diagnosis [3]; Prediction (general) [3]; Satellites [3]; Simulation [3]; Space applications [3]	2007 - 2011
Ecole Polytechnique de Montreal, QC, Canada[10]		Yacout S. [10]; Ghasemi, A. [6]; Ouali M. -S. [6]	Condition based maintenance (CBM) [10]; Engine maintenance [6]; Condition monitoring (CM) [5]; Hidden Markov models [5]; Bayes rule [4]; Proportional hazard model [4]; Bayesian methods [3]; Dynamic programming [3]; fault diagnosis [3]; Logical analysis of data [3]; Probability [3]	CBM [10]; Modeling [7]; Condition monitoring [6]; Engines [6]; Failure [5]; Degradation [4]; Diagnostics [3]; Fault diagnosis [3]; Maintenance policies [3]; Reliability [3]	2007 - 2011

Organization Name	Co-authoring Organizations	Top Authors	Top Keywords	Top Subject Groups	Publication Years
McGill University, Montreal, QC, Canada[7]	Defence R&D Canada (DRDC), Ottawa, ON, Canada [3]; National Research Council Canada, Boucherville, QC, Canada [3]	Jen, C.-K. [3]; Kobayashi, M. [3]; Mrad, Nezih [3]; Liu, W.-L. [2]; Mateescu, D. [2]; Misra, A. [2]; Wu, K.-T. [2]	Sensors [4]; Structural health monitoring (SHM) [4]; Aircraft [3]; Flexible ultrasonic transducer [3]; Sol-gel spray technique [3]; Ultrasonic transducers [3]; Aircraft detection [2]; Condition monitoring (CM) [2]; Couplants [2]; Crack detection [2]; Curved surfaces [2]; Damage detection [2]; Detection capability [2]; Flexible ultrasonic transducer array [2]; Monitoring and control [2]; Nondestructive examination [2]; piezoelectric sensors [2]; Pulse echoes [2]; Room temperature (RT) [2]; Structural engineering [2]; Titanium [2]; Transducers [2]; Ultrasonics [2]	Aircraft (excl. Rotorcraft) [5]; Structures [5]; Materials [4]; Piezoelectric devices [4]; Sensors [4]; SHM [4]; Ultrasonics [3]; Condition monitoring [2]; Cracks [2]; Damage detection [2]; Finite element methods (FEM) [2]; Inspection & nondestructive evaluation [2]; Manufacturing / production [2]	2007 - 2011

Organization Name	Co-authoring Organizations	Top Authors	Top Keywords	Top Subject Groups	Publication Years
University of Alberta, Edmonton, AB, Canada[7]		Zuo MJ [2]	Condition based maintenance (CBM) [2]; Condition monitoring (CM) [2]; Genetic algorithms [2]; Markov processes [2]; optimization model [2]; Structural health monitoring (SHM) [2]	Algorithms [3]; Artificial intelligence [3]; CBM [3]; Condition monitoring [2]; Diagnostics [2]; Reliability [2]; SHM [2]; Structures [2];	2008 - 2011
University of Ottawa, ON, Canada[7]	National Research Council Canada, Ottawa, ON, Canada [3]; Defence R&D Canada (DRDC), Ottawa, ON, Canada [2]	Guo, H. [2]; Nayak, A. [2]; Xiao, G. Z. [2]	Structural health monitoring (SHM) [6]; Damage detection [2]; Fiber Bragg Grating (FBG) [2]; Fiber optics [2]; Sensors [2]	SHM [6]; FBG sensors [3]; Fiber optics [3]; Sensors [3]; Aircraft (excl. Rotorcraft) [2]; Damage detection [2];	2006 - 2011
Ecole de Technologie Supérieure, Montreal, QC, Canada[6]		David E [4]; Godin T [3]; Bellemare J [2]; Lamarre L [2]; Nair A [2]	Condition based maintenance (CBM) [4]; machine insulation [4]; machine testing [4]; Diagnostic testing [3]; leakage currents [3]; Stators [3]; Ageing [2]; DC ramp test [2]; Insulation testing [2]; polarization-depolarization test [2]; ramped voltage test [2]; stator insulation system [2]	CBM [4]; Diagnostics [3]; Machinery [3]; Engines [2];	2006 - 2010

Organization Name	Co-authoring Organizations	Top Authors	Top Keywords	Top Subject Groups	Publication Years
National Research Council Canada, Boucherville, QC, Canada[6]	Defence R&D Canada (DRDC), Ottawa, ON, Canada [5]; McGill University, Montreal, QC, Canada [3]	Jen, C.-K. [6]; Kobayashi, M. [6]; Mrad, Nezih [5]; Wu, K.-T. [3]; Liu, W.-L. [2]	Ultrasonic transducers [5]; Sensors [4]; Sol-gel spray technique [4]; Structural health monitoring (SHM) [4]; Condition monitoring (CM) [3]; Damage detection [3]; Flexible ultrasonic transducer [3]; Health monitoring [3]; Nondestructive testing (NDT) [3]; sol-gel processing [3]; Structural engineering [3]	Structures [6]; Materials [5]; Ultrasonics [5]; Aircraft (excl. Rotorcraft) [4]; Piezoelectric devices [4]; Sensors [4]; SHM [4]; Condition monitoring [3]; Damage detection [3]; Health and usage monitoring [3];	2006 - 2011
University of Manitoba, Winnipeg, MB, Canada[6]		McNeill, D. K. [2]; Thomson, D. J. [2]	Condition monitoring (CM) [5]; Structural health monitoring (SHM) [4]; Neural networks [2]; Structural analysis [2]; Structural engineering [2]	Condition monitoring [5]; SHM [4]; Structures [4]; Artificial intelligence [2]; Sensors [2];	2006 - 2008
University of Waterloo, ON, Canada[6]			Condition monitoring (CM) [3]; Condition based maintenance (CBM) [2]; Structural engineering [2]	Condition monitoring [3]; Costs / ROI [3]; CBM [2]; Structures [2];	2008 - 2011

Organization Name	Co-authoring Organizations	Top Authors	Top Keywords	Top Subject Groups	Publication Years
Dalhousie University, Halifax, NS, Canada[5]		Newhook, J. [4]	Structural engineering [4]; bridges (structures) [3]; Condition monitoring (CM) [3]; Structural health monitoring (SHM) [3]; Concrete [2]; Cracks [2]; Fatigue testing [2]; Management systems [2]; Sensors [2]; slabs [2]	Civil structures / Bridges [5]; Structures [5]; Condition monitoring [3]; Sensors [3]; SHM [3]; Cracks [2]; Fatigue [2]; Ground vehicles [2]; Inspection & nondestructive evaluation [2]; Materials [2]	2006 - 2010

Table 7. Top Authors - International

Author	Affiliation	Co-Authors	Top Keywords	Top Subject Groups	Publication Years
Pecht, M.[45]	University of Maryland, College Park, MD, USA [26];	Pecht, M. [45]; Gu, J. [7]; Das, D. [5]; Kang, R. [5]; Niu, G. [5]	Prognostics and Health Management (PHM) [22]; Condition monitoring (CM) [17]; Health management system (HMS) [17]; Reliability [16]; Failure analysis [11]; prognostics [11]; Electronic product [10]; Engine maintenance [8]; Health monitoring [7]; Condition based maintenance (CBM) [6]; Effects analysis [6]	PHM [39]; Reliability [25]; Failure [23]; Condition monitoring [17]; Electronics [11]; Costs / ROI [9]; Engines [9]; Life cycle [9]; Diagnostics [8]; Health and usage monitoring [7]; Prediction (general) [7]	2006 - 2011
Goebel, K. F.[35]	NASA Ames Research Center, Moffett Field, CA, United States [11];	Goebel, K. F. [35]; Saha, B. [10]; Saha, S. [8]; Saxena, A. [7]; Celaya, J.R. [6]	Condition monitoring (CM) [12]; Engine maintenance [9]; particle filtering (numerical methods) [9]; Prognostics and Health Management (PHM) [9]; Remaining Useful Life (RUL) [9]; Condition based maintenance (CBM) [7]; prognostics [7]; Bayesian methods [6]; Health management system (HMS) [6]; remaining life assessment [6]	PHM [24]; Engines [14]; Condition monitoring [12]; RUL [12]; Algorithms [11]; Failure [11]; Electronics [9]; Aircraft (excl. Rotorcraft) [8]; CBM [8]; Diagnostics [7]	2006 - 2011

Author	Affiliation	Co-Authors	Top Keywords	Top Subject Groups	Publication Years
Takeda, N.[25]	University of Tokyo, Japan [18];	Takeda, N. [25]; Okabe, Y. [7]; Ozaki, T. [6]; Tajima, N. [6]; Takeya, H. [5]	Structural health monitoring (SHM) [18]; Fiber optic sensors [14]; Aircraft [13]; FBG sensors [12]; Condition monitoring (CM) [11]; Damage detection [11]; Fiber Bragg Grating (FBG) [11]; Bragg gratings [10]; Composite materials [9]; Fiber optics [9]	Sensors [24]; Structures [24]; Aircraft (excl. Rotorcraft) [19]; FBG sensors [19]; Fiber optics [19]; SHM [18]; Damage detection [13]; Condition monitoring [11]; Materials [11]; Strain [10]; Strain [6]	2006 - 2011
Ou, J. P.[24]	Harbin Institute of Technology, China [21];	Ou, J. P. [24]; Li Hongru [6]; Yu, Y. [6]; Zhao, X. [4]; Wang, Y. [3]; Zhou, Z. [3]	Structural health monitoring (SHM) [16]; Monitoring and control [11]; Condition monitoring (CM) [7]; Fiber Bragg Grating (FBG) [6]; bridges (structures) [5]; Sensors [5]; Civil infrastructure [4]; Damage detection [4]; Fiber optic sensors [4]; Fiber optics [4]; PVDF [4]	Structures [22]; SHM [16]; Civil structures / Bridges [13]; Sensors [12]; Strain [8]; Condition monitoring [7]; FBG sensors [6]; Fiber optics [6]; Wireless systems [5]; Corrosion [4]; Damage detection [4]; Fatigue [4]	2006 - 2011

Author	Affiliation	Co-Authors	Top Keywords	Top Subject Groups	Publication Years
Adams, D.[23]	Purdue University, West Lafayette, IN, USA [17];	Adams, D. [23]; Yoder, N. C. [5]; White JR [4]; Jata, K. V. [3]; Johnson, T. J. [3]; Mahulkar, V. V. [3]	Health monitoring [8]; Structural health monitoring (SHM) [8]; Condition monitoring (CM) [7]; Condition based maintenance (CBM) [6]; Damage detection [5]; Frequency response [5]; vibration [5]; Military vehicles [4]; Accelerometers [3]; Aircraft [3]; Computer simulation [3]; Crack detection [3]; Damage identification [3]; impact (mechanical) [3]; Mathematical models [3]; Mechanical damages [3]; Monitoring and control [3]; Nondestructive evaluation (NDE) [3]; Vehicles [3]	Structures [12]; Modeling [11]; SHM [9]; Health and usage monitoring [8]; Vibration [8]; Condition monitoring [7]; Damage detection [7]; Ground vehicles [7]; Impact damage [7]; CBM [6]; Cracks [6]; Military applications [6]	2006 - 2011

Author	Affiliation	Co-Authors	Top Keywords	Top Subject Groups	Publication Years
Bechhoefer, E.[22]	Goodrich Corporation, Vergennes, VT, United States [14];	Bechhoefer, E. [22]; He, D. [14]; Bernhard, A.P.F. [4]; Li, R. [3]; Mayhew, E. [3]; Wu, S. [3]	Health and Usage Monitoring Systems (HUMS) [11]; Condition monitoring (CM) [9]; Helicopters [7]; Structural health monitoring (SHM) [7]; Aircraft [6]; Condition indicators [6]; vibration [6]; Vibration data [5]; Remaining Useful Life (RUL) [4]; Aircraft maintenance [3]; Condition based maintenance (CBM) [3]; Flight critical components [3]; Health monitoring [3]	Health and usage monitoring [15]; Vibration [15]; HUMS [13]; Aircraft (excl. Rotorcraft) [10]; Condition monitoring [9]; Rotorcraft [7]; SHM [7]; Accidents / safety [5]; Diagnostics [5]; Algorithms [4]; PHM [4]; Prediction (general) [4]	2006 - 2011
Roemer, M. J.[22]	Impact Technologies, Rochester, NY, United States [22]	Roemer, M. J. [22]; Kalgren, P. W. [10]; Byington, C. S. [6]; Ginart, A. E. [6]; Brown, D. [4]	Prognostics and Health Management (PHM) [8]; Condition monitoring (CM) [5]; Power drives [4]; prognostics [4]; Software [4]; Actuators [3]; Condition based maintenance (CBM) [3]; Electric machines [3]; Electronic prognostics [3]; Failure analysis [3]; Health management system (HMS) [3]; Sensors [3]; signal processing [3]; Testing [3]	PHM [12]; Diagnostics [7]; Electronics [6]; Engines [6]; Condition monitoring [5]; Failure [5]; Health and usage monitoring [5]; Modeling [5]; Algorithms [4]; Machinery [4]	2006 - 2010

Author	Affiliation	Co-Authors	Top Keywords	Top Subject Groups	Publication Years
Byington, C. S.[21]	Impact Technologies, Rochester, NY, United States [13];	Byington, C. S. [21]; Watson, M. J. [7]; Roemer, M. J. [6]; Kalgren, P. W. [5]; Smith MJ [3]; Vachtsevanos, G. J. [3]	Condition monitoring (CM) [8]; Aircraft maintenance [7]; Prognostics and Health Management (PHM) [7]; Health management system (HMS) [6]; Engine maintenance [5]; fault diagnosis [5]; Health monitoring [5]; Condition based maintenance (CBM) [4]; prognostics [4]; Remaining Useful Life (RUL) [4]	PHM [15]; Aircraft (excl. Rotorcraft) [13]; Engines [12]; Condition monitoring [8]; Diagnostics [8]; Failure [5]; Fault diagnosis [5]; Health and usage monitoring [5]; RUL [5]; Vibration [5]	2006 - 2011
Vachtsevanos, G. J.[21]	Georgia Institute of Technology, Atlanta, GA, United States [9];	Vachtsevanos, G. J. [21]; Orchard M. [8]; Patrick, R. [8]; Zhang, B. [8]; Kacprzynski, G. J. [6]	fault diagnosis [13]; Condition monitoring (CM) [8]; particle filtering (numerical methods) [7]; Condition based maintenance (CBM) [6]; Aircraft [5]; Bayesian methods [5]; Engine maintenance [5]; Feature extraction [5]; Helicopters [5]; Remaining Useful Life (RUL) [5]	Diagnostics [15]; Fault diagnosis [14]; PHM [12]; Aircraft (excl. Rotorcraft) [8]; Condition monitoring [8]; Failure [8]; CBM [7]; Data processing [6]; Engines [6]; Rotorcraft [5];	2006 - 2011

Author	Affiliation	Co-Authors	Top Keywords	Top Subject Groups	Publication Years
Worden, K.[21]	University of Sheffield, United Kingdom [18];	Worden, K. [21]; Manson, G. [10]; Barthorpe, R. J. [5]; Farrar, C. R. [4]; Hensman, J. [3]; Papatheou, E. [3]; Pierce, S. G. [3]; Staszewski, W. J. [3]	Structural health monitoring (SHM) [18]; Condition monitoring (CM) [11]; Damage detection [10]; Aircraft [8]; Aerospace components [7]; Aircraft wing [6]; Structures (built objects) [6]; Feature extraction [5]; Damage location [4]; Feature selection [4]; Training data [4]	SHM [18]; Structures [17]; Aircraft (excl. Rotorcraft) [15]; Condition monitoring [11]; Damage detection [10]; Artificial intelligence [5]; Materials [5]; Fatigue [4]; Inspection & nondestructive evaluation [4]; Ultrasonics [4]	2007 - 2011
Farrar, C. R.[19]	Los Alamos National Laboratory, Los Alamos, NM, USA [10];	Farrar, C. R. [19]; Park, G. [12]; Todd, M. D. [8]; Kosmatka, J. B. [5]; Oliver, J. A. [4]; Worden, K. [4]	Structural health monitoring (SHM) [15]; Condition monitoring (CM) [7]; Finite element analysis [6]; Remotely operated vehicles [6]; Aerospace components [5]; Feature extraction [5]; Sensors [5]; Structural engineering [5]; Unmanned aerial vehicles (UAV) [5]; Damage detection [4]; Finite element (FE) modeling [4]; Monitoring and control [4]	SHM [16]; Structures [14]; Sensors [9]; Condition monitoring [7]; Remotely operated vehicles [7]; Aircraft (excl. Rotorcraft) [6]; Damage detection [6]; Finite element methods (FEM) [6]; Modeling [6]; Communication systems [4]; Materials [4]	2006 - 2011

Author	Affiliation	Co-Authors	Top Keywords	Top Subject Groups	Publication Years
Giurgiutiu, V.[18]	University of South Carolina, Columbia, SC, USA [15];	Giurgiutiu, V. [18]; Lingyu Yu [8]; Lin, B. [3]; Xu, B. [3]; Ziehl, P.H. [3]	Structural health monitoring (SHM) [16]; Condition monitoring (CM) [10]; Piezoelectric wafer active sensors [7]; Lamb waves [6]; Structural engineering [6]; Acoustic emissions (AE) [5]; Damage detection [5]; Nondestructive evaluation (NDE) [5]; Piezoelectric devices [5]; bridges (structures) [4]; Corrosion [4]; Cracks [4]; Nondestructive testing (NDT) [4]; Piezoelectric (PZT) [4]; Piezoelectric wafer active sensors (PWAS) [4]	SHM [16]; Sensors [15]; Structures [14]; Piezoelectric devices [13]; Condition monitoring [10]; Ultrasonics [8]; Damage detection [7]; Inspection & nondestructive evaluation [7]; Cracks [6]; Materials [6]	2006 - 2011

Author	Affiliation	Co-Authors	Top Keywords	Top Subject Groups	Publication Years
Inman, D. J.[18]	Virginia Polytechnic Institute and State University, Blacksburg, VA, USA [14];	Inman, D. J. [18]; Park, S. [6]; Yun, C.-B. [5]; Dong, Sam Ha [4]; Grisso BL [3]	Structural health monitoring (SHM) [14]; Condition monitoring (CM) [9]; Damage detection [7]; Piezoelectric (PZT) [5]; Sensors [5]; Cracks [4]; piezoelectric sensors [4]; Piezoelectric transducers [4]; Corrosion [3]; Electric impedance [3]; Inspection [3]; Piezoelectric devices [3]; Structural engineering [3]; Structures (built objects) [3]	SHM [17]; Structures [15]; Condition monitoring [9]; Damage detection [9]; Sensors [9]; Materials [6]; Piezoelectric devices [6]; Cracks [5]; Wireless systems [5]; Aircraft (excl. Rotorcraft) [4]; Corrosion [4]	2006 - 2011

Table 8. Top Canadian Authors

Author Name	Affiliation	Top Co-Authors	Top Subject Terms	Top Subject Groups	Publication Years
Mrad, Nezih[16]	Defence R&D Canada (DRDC), Ottawa, ON, Canada [16];	Mrad, Nezih [16]; Jen, C.-K. [5]; Kobayashi, M. [5]; Xiao, G. Z. [4]; Wu, K.-T. [3]	Condition monitoring (CM) [8]; Structural health monitoring (SHM) [8]; Ultrasonic transducers [6]; Aircraft [5]; Structural engineering [5]; Aerospace components [4]; Aircraft maintenance [4]; Damage detection [4]; Nondestructive testing (NDT) [4]; Sensors [4]; Sol-gel spray technique [4]	Aircraft (excl. Rotorcraft) [12]; Sensors [10]; Structures [10]; SHM [9]; Condition monitoring [8]; FBG sensors [6]; Fiber optics [6]; Ultrasonics [6]; Inspection & nondestructive evaluation [5]; Materials [5];	2006 - 2011

Author Name	Affiliation	Top Co-Authors	Top Subject Terms	Top Subject Groups	Publication Years
Jardine, A. K. S.[10]	University of Toronto, ON, Canada [10]	Jardine, A. K. S. [10]; Banjevic, D. [8]; Lin, D. [2]; Zuashkiani A [2]	Condition based maintenance (CBM) [7]; Condition monitoring (CM) [5]; Engine maintenance [5]; Decision making [3]; Optimization [3]; Proportional hazard model [3]; Bayes rule [2]; Bayesian methods [2]; condition based maintenance optimization [2]; Condition indicators [2]; Covariates [2]; Failure analysis [2]; Hazards [2]; knowledge elicitation process [2]; Potential benefits [2]; Power transformer [2]; Remaining Useful Life (RUL) [2]; time dependent covariates [2]; vibration [2]	CBM [9]; Failure [6]; Condition monitoring [5]; Engines [5]; Decision support [3]; PHM [3]; Vibration [3]; Accidents / safety [2]; Data processing [2]; Machinery [2]; Machinery [2]; Oil / lubrication [2]; Prediction (general) [2]	2006 - 2011

Author Name	Affiliation	Top Co-Authors	Top Subject Terms	Top Subject Groups	Publication Years
Yacout S.[10]	Ecole Polytechnique de Montreal, QC, Canada [10]	Yacout S. [10]; Ghasemi, A. [6]; Ouali M. -S. [6]	Condition based maintenance (CBM) [10]; Engine maintenance [6]; Condition monitoring (CM) [5]; Hidden Markov models [5]; Bayes rule [4]; Proportional hazard model [4]; Bayesian methods [3]; Dynamic programming [3]; fault diagnosis [3]; Logical analysis of data [3]; Probability [3]	CBM [10]; Modeling [7]; Condition monitoring [6]; Engines [6]; Failure [5]; Degradation [4]; Diagnostics [3]; Fault diagnosis [3]; Maintenance policies [3]; Reliability [3]	2007 - 2011
Makis V.[9]	University of Toronto, ON, Canada [9]	Makis V. [9]; Jianmou Wu [2]; Yin Z. [2]	Condition based maintenance (CBM) [8]; Condition monitoring (CM) [3]; Control charts [3]; Algorithms [2]; Bayesian control chart [2]; Bayesian methods [2]; Comparison result [2]; Economic statistical design [2]; Engine maintenance [2]; Failure state [2]; Statistical process control [2]	CBM [9]; Condition monitoring [4]; Modeling [3]; Algorithms [2]; Costs / ROI [2]; Decision support [2]; Engines [2]; Failure [2]; Fault detection [2]; Maintenance policies [2]	2006 - 2011

Author Name	Affiliation	Top Co-Authors	Top Subject Terms	Top Subject Groups	Publication Years
Banjevic, D.[8]	University of Toronto, ON, Canada [8]	Banjevic, D. [8]; Jardine, A. K. S. [8]; Lin, D. [2]; Zuashkiani A [2]	Condition based maintenance (CBM) [6]; Condition monitoring (CM) [3]; Engine maintenance [3]; Bayes rule [2]; Bayesian methods [2]; Condition indicators [2]; Covariates [2]; Decision making [2]; knowledge elicitation process [2]; Potential benefits [2]; Proportional hazard model [2]; Remaining Useful Life (RUL) [2]; time dependent covariates [2]	CBM [7]; Failure [4]; Condition monitoring [3]; Engines [3]; PHM [3]; Decision support [2]; Machinery [2]; RUL [2]; Vibration [2];	2006 - 2011
Tian, Zhigang[7]	Concordia University, Montreal, QC, Canada [7]	Tian, Zhigang [7]; Jin, T. [3]; Zuo MJ [2]	Condition monitoring (CM) [7]; Condition based maintenance (CBM) [6]; Engine maintenance [5]; Artificial neural network (ANNs) [3]; Maintenance cost [3]; Monitoring and control systems [3]; Multiple components [3]; Neural networks [3]; Simulation [3]; Turbine components [3]; Wind farm [3]; Wind power generation systems [3]; Wind turbines [3]	Condition monitoring [7]; CBM [6]; Artificial intelligence [5]; Costs / ROI [5]; Engines [5]; Prediction (general) [3]; Simulation [3]; Vibration [3]; Decision support [2]; Failure [2];	2009 - 2011

Author Name	Affiliation	Top Co-Authors	Top Subject Terms	Top Subject Groups	Publication Years
Ghasemi, A.[6]	Ecole Polytechnique de Montreal, QC, Canada [6]	Ghasemi, A. [6]; Ouali M. -S. [6]; Yacout S. [6]	Condition based maintenance (CBM) [6]; Bayes rule [4]; Hidden Markov models [4]; Proportional hazard model [4]; Bayesian methods [3]; Dynamic programming [3]; Engine maintenance [3]; Probability [3]; Condition monitoring (CM) [2]; Failure analysis [2]; Hazards [2]; Replacement policy [2]; system failure rate [2]	CBM [6]; Modeling [5]; Failure [4]; Condition monitoring [3]; Degradation [3]; Engines [3]; Maintenance policies [3]; Costs / ROI [2]; Reliability [2];	2007 - 2010
Jen, C.-K.[6]	National Research Council Canada, Boucherville, QC, Canada [6]; Defence R&D Canada (DRDC), Ottawa, ON, Canada [5]; McGill University, Montreal, QC, Canada [3]	Jen, C.-K. [6]; Kobayashi, M. [6]; Mrad, Nezih [5]; Wu, K.-T. [3]; Liu, W.-L. [2]	Ultrasonic transducers [5]; Sensors [4]; Sol-gel spray technique [4]; Structural health monitoring (SHM) [4]; Condition monitoring (CM) [3]; Damage detection [3]; Flexible ultrasonic transducer [3]; Health monitoring [3]; Nondestructive testing (NDT) [3]; sol-gel processing [3]; Structural engineering [3]	Structures [6]; Materials [5]; Ultrasonics [5]; Aircraft (excl. Rotorcraft) [4]; Piezoelectric devices [4]; Sensors [4]; SHM [4]; Condition monitoring [3]; Damage detection [3]; Health and usage monitoring [3];	2006 - 2011

Author Name	Affiliation	Top Co-Authors	Top Subject Terms	Top Subject Groups	Publication Years
Kobayashi, M.[6]	National Research Council Canada, Boucherville, QC, Canada [6]; Defence R&D Canada (DRDC), Ottawa, ON, Canada [5]; McGill University, Montreal, QC, Canada [3]	Jen, C.-K. [6]; Kobayashi, M. [6]; Mrad, Nezih [5]; Wu, K.-T. [3]; Liu, W.-L. [2]	Ultrasonic transducers [5]; Sensors [4]; Sol-gel spray technique [4]; Structural health monitoring (SHM) [4]; Condition monitoring (CM) [3]; Damage detection [3]; Flexible ultrasonic transducer [3]; Health monitoring [3]; Nondestructive testing (NDT) [3]; sol-gel processing [3]; Structural engineering [3]	Structures [6]; Materials [5]; Ultrasonics [5]; Aircraft (excl. Rotorcraft) [4]; Piezoelectric devices [4]; Sensors [4]; SHM [4]; Condition monitoring [3]; Damage detection [3]; Health and usage monitoring [3];	2006 - 2011
Ouali M. -S.[6]	Ecole Polytechnique de Montreal, QC, Canada [6]	Ghasemi, A. [6]; Ouali M. -S. [6]; Yacout S. [6]	Condition based maintenance (CBM) [6]; Bayes rule [4]; Hidden Markov models [4]; Proportional hazard model [4]; Bayesian methods [3]; Dynamic programming [3]; Engine maintenance [3]; Probability [3]; Condition monitoring (CM) [2]; Failure analysis [2]; Hazards [2]; Replacement policy [2]; system failure rate [2]	CBM [6]; Modeling [5]; Failure [4]; Condition monitoring [3]; Degradation [3]; Engines [3]; Maintenance policies [3]; Costs / ROI [2]; Reliability [2];	2007 - 2010

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Condition Based Maintenance Literature Review

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The goal of this document is to provide Condition Based Maintenance (CBM) stakeholders with a solid perspective on the state-of-the-art of CBM and to inform the Canadian Forces on the potential of CBM and Autonomic Logistics (AL) practices for improved military platform performance and cost effective platform life cycle management. Two databases of 4,394 bibliographic records of journal articles, conferences papers, theses and government reports (2006- 2011) and 1,204 patent families (1990-2011) were compiled and analyzed using text analytic software. Findings show that CBM research is primarily engaged with technical challenges related to sensor technologies, condition monitoring, and diagnostic and prognostic accuracy. Communications and decision support technologies are also receiving increased attention. The benefits of CBM are substantial and could represent significant cost-efficiencies in the long-term. However, short-term benefits are difficult to realize since initial acquisition and installation costs are high. Careful consideration must be paid to data integration with legacy systems, particularly supply chain management and logistics systems. Work on the Joint Strike Fighter (JSF) is advancing development of prognostics and health management (PHM) methods as well as the related logistics systems, and is an important area to monitor as lessons learned for the JSF could be applied to retrofitting legacy platforms.

Le présent document a pour but de fournir aux intervenants de la maintenance selon l'état (MSE) un tour d'horizon fidèle des derniers avancements dans ce domaine, ainsi que d'informer les Forces canadiennes (FC) sur les pratiques possibles en matière de MSE et de logistique autonome (LA) menant à des plateformes militaires plus performantes et à une gestion rentable de leur cycle de vie. Deux bases de données, l'une comptant 4 394 registres bibliographiques d'article de périodiques, de communications de conférence, de thèses de doctorat et de rapports gouvernementaux (2006-2011) et l'autre plus de 1 204 familles de brevets (1990-2011), ont été compilées et analysées au moyen de logiciels d'analyse textuelle. Les résultats montrent que la recherche en MSE fait surtout face à des défis touchant les technologies des capteurs, la surveillance de l'état et l'exactitude des diagnostics et des pronostics. L'on constate également que les technologies de la communication et de l'aide à la prise de décision retiennent de plus en plus l'attention. Les avantages de la MSE sont indéniables et peuvent se traduire par des économies substantielles à long terme. En revanche, les avantages à court terme sont hypothéqués par l'importance des coûts initiaux d'acquisition et d'installation. Il faut examiner soigneusement l'intégration des données avec les systèmes existants, en particulier ceux de la gestion de la chaîne d'approvisionnement et de la logistique. Les travaux portant sur le chasseur Joint Strike Fighter (JSF), qui favorisent l'élaboration de méthodes de pronostic et de gestion de l'état et le développement des systèmes de logistique connexes, sont un terreau fertile à surveiller en termes de leçons retenues, puisqu'on pourrait en appliquer les résultats à la modernisation des plateformes existantes.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus, e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

Condition based maintenance; structural health monitoring; prognostics health management; autonomic logistics; return on investment; sensor technologies; decision support; sense and respond logistics; asset visibility; RFID; supply chain.